Report No. FAA-RD-78-9

LEVEL

12

AD A071057

PILOTED FLIGHT SIMULATION STUDY OF LOW-LEVEL WIND SHEAR, PHASE 3

ALL-WEATHER LANDING SYSTEMS, ENGINEERING SERVICES SUPPORT PROJECT, TASK 2

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March 1978

Interim Report

Document is available to the U.S. public through
the National Technical Information Service,
Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

DISCLAIMER NOTICE

NOTICE

(19) 78-9

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
(18) FAA-RD-[redacted]-9 (78)		

4. Title and Subtitle (6)

PILOTED FLIGHT SIMULATION STUDY OF LOW-LEVEL WIND SHEAR, PHASE 3, All-Weather Landing Systems, Engineering Syrvices Support Project, Task 2.

AD4 7985

5. Report Date (11) Marc[redacted]78

6. Performing Organization Code

8. Performing Organization Report No. SRI Project 4364

7. Author(s) (10) W. B./Gartner, D. M./Condra, W. H./Foy, W. O./Nice, C. E./Wischmeyer

9. Performing Organization Name and Address

SRI International
Aviation Systems Laboratory
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10. Work Unit No. (TRAIS)

11. Contract or Grant No. (15) DOT-FA75WA-3650

13. Type of Report and Period Covered (9) Interim Report. Apr[redacted] - Dec[redacted]77

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D.C. 20590

14. Sponsoring Agency Code FAA/ARD-743

15. Supplementary Notes

Prepared on ALL-WEATHER LANDING SYSTEMS, Engineering Services Support, Project 4364, Task 2

(12) 123p.

16. Abstract

This task is concerned with the development and test by piloted flight simulation of airborne techniques designed to aid the pilot to detect and cope with low-level wind shear. This report documents the Phase 3 tests on a DC-10 aircraft simulator, involving a set of wind profiles significantly expanded over those used previously and an especially large group (26) of subject pilots in the major test.

The operational situation simulated was a landing under Category I visibility to a 7000-ft runway with ILS guidance. There were 10 different wind profiles, with wind shear ranging from low to high severity. In ~~the first exercise was~~ an Initial Trial ~~in which~~ various aiding concepts were compared in individual experiments. This involved 4 versions of groundspeed displays, 2 versions of modified (acceleration-augmented) flight director steering and speed commands, and 2 go-around decision aids: a computation of longitudinal acceleration margin and an energy-rate meter. The more promising were combined in 3 systems ~~which were~~ tested in a Full Trial.

Performance was marginal, but would have been adequate if all the go-around advisories had been honored. False-alarm and missed-alarm rates of the advisories were too high. Additional work was recommended on go-around decision aids, the important of effective go-around decision aids being emphasized. It was noted that the go-around warning requires improved consistency in backup information; an on-off display is not adequate.

This work was accomplished by the AWLS team (SRI, Bunker Ramo Corp., Collins Avionics Group) with Douglas Aircraft Co. as simulation subcontractor.

17. Key Words		18. Distribution Statement
wind shear	DC-10 flight simulation	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia, 22161.
groundspeed	go-around aid	
flight director		
airborne instrumentation		

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	122	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

411 271

METRIC CONVERSION FACTORS

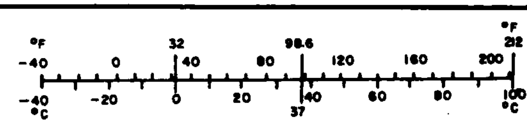
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The purpose of Task 2 of the All-Weather Landing Systems (AWLS) project is to develop and implement a manned flight simulation program to (1) investigate terminal flight operations, emphasizing wind shear effects, and (2) determine the operational and technical role of head-up displays. This interim report describes the results obtained by the AWLS team--SRI, Bunker Ramo Corporation, and Collins Avionics Group of Rockwell International --on an advanced test with a DC-10-10 aircraft simulator of the capabilities of certain aiding concepts to assist the pilot in coping with low-level wind shear, particularly on approach and landing. The aids were based on airborne instrumentation and the information was displayed on the instrument panel. Tests were made of go-around decision aids as well as approach management techniques. The sponsoring organizations are FAA Wind Shear Program Office and ARD-740; the Technical Monitor is W. J. Cox.

TABLE OF CONTENTS

I INTRODUCTION 1

A. Program, Objectives and Approach 1
B. Organization of Report 5

II METHOD 7

A. Simulator Configuration 7
B. Wind Profiles for Simulation Tests 11
C. Evaluation Plan 12

III INITIAL TRIALS 17

A. Groundspeed Concepts 17
B. Modified Flight Director Concepts 27
C. Go-Around Advisory Concepts 36

IV FULL TRIAL 47

A. Systems Tested 47
B. Evaluation Plan 48
C. Approach and Landing Outcomes 53

V CONCLUSIONS AND RECOMMENDATIONS 91

A. Conclusions Based on Initial Trial 91
B. Conclusions Based on Full Trial 93
C. Recommendations 94

APPENDICES

A. Description of Wind Shear Profiles 97
B. On-Site Data Recording 108

REFERENCES 115

ILLUSTRATIONS

1. Douglas Moving Base Development Flight Simulator 8
2. Simulated DC-10 Cockpit 9
3. Sample Summary Data Printout 16
4. Airspeed/Groundspeed Display with Fast/Slow 18

5. Computational Algorithm for Deriving the Modified Fast/Slow Speed Command 20

6. Digital Readout of Groundspeed 21

7. Simplified Control Law for Modified Flight Director 28-29

8. Baseline DC-10 Flight Director 30-31

9. Modified Speed Axis Control Law MFDT-1 (Without Groundspeed Information) 32

10. Modified Speed Axis Control Law MFDT-2 with Diminishing Headwind Shear Compensation 33

11. Douglas Energy Rate Instrument 39

12. Performance of Go-Around Decision Aids 43

13. System GNS-3/ENR 49

14. System GNS-6/ΔA 50

15. System MFDT-2/ENR 51

16. Landing Outcomes 56-57

17. Position Dispersions at Inner Marker with GNS-3/ENR 60

18. Position Dispersions at Inner Marker with GNS-6/ΔA 61

19. Position Dispersions at Inner Marker with MFDT-2/ENR . . . 62

20. Position Dispersions at Touchdown with GNS-3/ENR 63

21. Position Dispersions at Touchdown with GNS-6/ΔA 64

22. Position Dispersions at Touchdwon with MFDT-2/ENR 65

23. Airspeed Management During the Low-level Shear Encounters Using Each Aid 68

24. Maximum Drop in Groundspeed Over the 500 to 100-Foot Approach Segment 70

25. Effects of Airspeed Management Techniques on Touchdown Position and Groundspeed 71

26. Glide Slope Tracking Accuracy During Low-level Shear Encounters 73

27. Localizer Tracking Accuracy During Low-level Shear Encounters 74

28. Accuracy of Flight Director Command Following During Low-level Shear Encounters 75

29. Control Activity During Low-level Shear Encounters 77

30. Typical Aircraft Response to Low-level Wind Shear on Takeoff and Climbout 85-89

A-1. Wind Profile 1, Approach on 3° Glide Path 100

A-2. Wind Profile 5, Approach on 3° Glide Path 100

A-3. Wind Profile 7, Approach on 3^{o} Glide Path 101
A-4. Wind Profile 8, Approach on 3^{o} Glide Path 101
A-5. Wind Profile 2, Approach on 3^{o} Glide Path 102
A-6. Wind Profile 9, Approach on 3^{o} Glide Path 102
A-7. Wind Profile 6, Approach on 3^{o} Glide Path 103
A-8. Wind Profile 10, Approach on 3^{o} Glide Path 103
A-9. Wind Profile 4, Approach on 3^{o} Glide Path 104
A-10. Wind Profile 3, Approach on 3^{o} Glide Path 104
A-11. Wind Profile 11, Takeoff with 6^{o} Climbout 105
A-12. Wind Profile 12, Takeoff with 6^{o} Climbout 105
A-13. Wind Profile 13, Takeoff with 6^{o} Climbout 106
A-14. Wind Profile 14, Takeoff with 6^{o} Climbout 106
A-15. Wind Profile 15, Takeoff with 6^{o} Climbout 107

TABLES

1. Subject Pilots 6
2. Simulator Motion Limits 10
3. Experimental Design for the Groundspeed Experiment 23
4. Order of Pilot Assignment to Alternative Groundspeed Concepts 23
5. Summary of Approach and Landing Outcomes in the Initial Testing of Groundspeed Display Concepts 25
6. Inner-Marker Limits 26
7. Landing-Outcome Limits 26
8. Order of Pilot Exposure to Alternative MFD Concepts 34
9. Summary of Approach and Landing Outcomes in the Initial Testing of Alternative MFD Thrust Commands 35
10. Plan for the Go-Around Advisory Experiment 41
11. Order of Pilot Exposure to Alternative Go-Around Advisory Concepts 41
12. Summary of Approach and Landing Outcomes in the Initial Testing of Go-Around Advisories 44
13. Comparative Performance of Alternative Techniques for Providing Go-Around Advisories 45
14. Test Plan for Full-Scale Testing of Selected Systems . . . 52

15. Wind Shear Profiles Selected for Full-Scale Testing 54

16. Summary Data on Approach and Landing Outcomes for the Full-Scale Testing of Selected Aids 59

17. Validity of Go-Around Advisory Announcements for Each Aiding Concept by Level of Shear Severity 67

18. Pilot Workload Ratings 78

19. Pilot Acceptance Ratings 79

20. Summary Data on Aircraft Response to Wind Shear Encounters for Seven Attempted Takeoffs 90

A-1. Summary of Wind Profiles Used in Piloted Simulations . . . 99

B-1. Flight Situation Parameters Recorded on Magnetic Tape . . . 109

B-2. Flight Situation Parameters Recorded on Strip Charts . . . 111

B-3. Data Entries of the Summary Printout 112

I INTRODUCTION

A. Program, Objectives and Approach

The flight simulation test reported here is an element of the major FAA program that has the objectives of examining the hazards associated with wind shear in the terminal area, developing solutions to the wind shear problem, implementing such solutions and integrating them into the National Airspace System. One segment of the program is designed to investigate potential solutions in the category of airborne equipment. In this approach a series of manned flight simulation exercises have been conducted for the FAA.

The first exercise[1*] was conducted in April and May of 1976 by the AWLS team: SRI and Bunker Ramo Corporation (BR). The simulation support subcontractor was Douglas Aircraft Company, McDonnell-Douglas Corporation, Long Beach, California, and a DC-10 training simulator was used. This was an exploratory exercise that examined the hazard presented by wind shear in various approach and landing situations, and made a screening evaluation of a variety of possible techniques for aiding the pilot; 8 subject pilots "flew" against 4 wind profiles, 3 with significant shear. In July, 1976, the FAA Simulation Branch, ARD-540, conducted a similar exploratory exercise with a B-737 model in the Flight Simulator for Advanced Aircraft (FSAA) at the National Aeronautics and Space Administration, Ames Research Center. There were 11 subject pilots and 3 wind shear profiles. These two tests indicated a number of aiding techniques that held promise for further trial. A Phase 2 study[2] was conducted by SRI and BR in the period November 1976, through January 1977. The simulation subcontractor was Douglas again; a DC-10-10 aircraft was modeled in the Douglas Moving Base Development Flight Simulator (MBDFS). Using 4 wind profiles, 3 with shear, and a total of 16 subject pilots, we ran three distinct experiments to test

[*] References are listed at the end of this report.

potential aiding concepts against conventional current approach management: aids based on groundspeed, aids based on flight path angle, and a design for modified (acceleration-augmented) flight director steering commands developed by Collins Avionics Group, Rockwell International, of the AWLS team. The best performance was shown by a two-needle display of airspeed and groundspeed, and by the Collins modified flight director; both techniques were significantly better than the conventional (i.e., baseline).

These studies, with supporting work by the AWLS team and with independent wind shear investigations by others, form the background for the Phase 3 tests. The purpose of these tests was to evaluate the capabilities of improved groundspeed displays and acceleration-augmented flight directors to provide solutions to wind sheer encounters for commercial wide-body turbojet aircraft. In addition, candidate aids for making the go-around decision were evaluated. The tests were designed to include an expanded collection of wind profiles. The exercise was conducted in two parts: an Initial Trial in which various forms of the techniques were compared, and a Full Trial in which the most promising techniques and displays were combined to form candidate systems and were tested in combination.

Development work for the exercise began in April 1977. Collins initiated a study of acceleration-augmented flight director thrust commands for coping with wind shear and their integration with the steering commands of the modified flight director. SRI and BR undertook improvement of the groundspeed algorithms and study of go-around decision aids. On 25 April a letter was sent to Douglas requesting a proposal for simulation support. Sole-source procurement was justified because of the availability at Douglas of their MBDFS in DC-10 configuration, the existence in the Douglas simulator of necessary software, and our good experience with Douglas in earlier work. They responded on 27 May with their proposal 77D-177T. It was evaluated, it was found to be responsive and the subcontract was negotiated. A test plan in summary form was submitted to the FAA on 15 July. On 22 July a project meeting with Douglas

and the AWLS team was held at Long Beach, and Douglas was authorized to start work. Collins delivered the modified flight director thrust and steering commands on 8 August. Software checkout on the MBDFS started on 15 August, and moving-base checks began on 22 August. A detailed test plan with specifications for the aiding concepts to be tested was submitted to the FAA on 23 August. BR completed the briefing and debriefing materials for the subject pilots, and BR project pilots made checkout simulator runs on 6 September. The Initial Trials started on the 7th. During 7-9 September, 4 subject pilots ran two experiments, one comparing 4 versions of ground speed displays and one comparing 2 different designs of acceleration-augmented flight directors. A pilot "flew" 8 wind profiles with shear, 4 training and 4 for technique performance evaluation, with each aiding concept. In the week 12-15 September, 4 more subject pilots tested go-around decision aids in an experiment with the same 8 wind profiles, 4 for training and 4 for test. The aiding concepts were compared with baseline; 3 techniques, one procedural and 2 incorporating special displays, were tested individually and the 2 special displays were each tested in combination with an approach management aid. This completed the Initial Trial which provided 384 runs, 192 training and 192 for data. About 49 simulator hours were required.

After review of the results, 3 combinations of aids were selected as systems to be tested in the Full Trial:

(1) Groundspeed displayed on the V_{mo} needle of the airspeed indicator; groundspeed error incorporated in the flight director thrust command; display of rate-of-change of energy as go-around decision aid.

(2) Digital readout of groundspeed; groundspeed error incorporated in the flight director thrust command; go-around warning light indicating a negative margin of available acceleration compared to acceleration demanded by the wind shear.

(3) Modified (acceleration-augmented) flight director with steering and thrust commands integrated by Collins; digital readout of groundspeed; display of rate-of-change of energy as go-around decision aid.

In addition to the tests of these systems, some runs were made on takeoffs in wind shear for hazard investigation and a short trial was made of a wind shear instrument supplied by Captain Jack H. Bliss of Flying Tiger Line. The Full Trial was started on 4 October, was interrupted on the 13th for movie filming, and was completed on 21 October. A total of 24 subject pilots "flew" each of the aiding systems on approach and landing against 8 wind profiles, at least 4 for training (more training runs were provided if the subject pilot requested them) and 4 for system evaluation; 2 more subject pilots "flew" systems (2) and (3) in a similar series. This provided 304 data runs for system evaluation, 308 training runs, 46 takeoff runs, and 53 runs on the Bliss instrument. The total was 711 simulator runs in about 91 hours, not including runs for movies and for informal demonstrations and checkout.

On 15-17 November, presentations of the preliminary results of both trials and demonstration runs (about 24 hours) on the MBDFS were made at Long Beach for visitors from the FAA, U.S. Air Force, NASA, National Transportation Safety Board, Allegheny Airlines, American Airlines, Continental Air Lines, Eastern Air Lines, National Airlines, Ozark Air Lines, Trans World Airlines, United Air Lines, British Airways, Air Transport Association, Air Line Pilots Association, Allied Pilots Association, Boeing Company, Lockheed Corporation, Douglas, ARMA Corporation, General Electric Company, Bliss Aviation, BR and Collins. The simulation exercise was completed on 18 November 1977 with additional runs for technical movie films.

The AWLS project is under the supervision of Mr. Dean F. Babcock (SRI). The leader for this Task 2 simulation and developmental effort was Dr. Wade H. Foy (SRI). At SRI, Mr. Walter B. Gartner designed the experiments and contributed to the evaluation of the results; Messrs. David W. Ellis, Michael G. Keenan and Robert D. Daniel did the data reduction and analysis. Dr. A. C. McTee led the BR effort and was test director for the experiments; Captain William O. Nice and Colonel Don M. Condra of BR were observers for the tests and acted as first officers for the runs. All

three contributed to the evaluation of the experimental results. At Collins, work on the modified flight director algorithms was under the supervision of Mr. Jim L. Foster; Mr. E. Dave Skelley was Collins project leader and Mr. C. P. Shih was project engineer. The Douglas simulation support was managed by Mr. John D. McDonnell and Mr. Charles M. Anderson; Mr. Ernest Admiral was responsible for simulator test integration, and Mr. Paul L. Jernigan was responsible for simulator software. Successfull completion of the test schedule was due primarily to the enthusiasm and cooperation of the BR and Douglas teams.

The list of pilots who acted as subjects for the tests runs is given in Table 1. The FAA was responsible for pilot recruiting; assistance was provided by the Air Line Pilots Association, the Air Transport Association and the AWLS team. The list shows a wide range of participation by the aviation community: FAA Western Region, U.S. Air Force, airlines, and airframe manufacturers. The subject pilots served without remuneration from the project, and the test exercise owes a great measure to their professional competence and dedicated efforts.

B. Organization of Report

This report follows the organizational structure of the test exercise. The section on "methods," which follows, describes the experimental procedures and conditions: simulator characteristics, wind models, data acquisition and recording. The Initial Trial is discussed in Section III, including descriptions of the aiding concepts tested, the design of the three experiments and a review of the results. Section IV gives a description of the three systems tested in the Full Trial, presents the plan for the test and gives the detailed test results. The conclusions drawn from the experimental results and recommendations to the FAA are presented in Section V. Various technical details and supporting documents are in the appendices.

Table 1

SUBJECT PILOTS

Initial Trial

Mr. Don D. Alexander, FAA Flight Test
Capt. Will A. Brown, Pan American World Airways
Mr. Ralph C. Cokeley, Lockheed Corporation
Capt. George A. Hof, Jr., American Airlines
Mr. E. W. Johnson, FAA
Mr. H. H. Knickerbocker, Douglas Aircraft Company
Capt. R. E. Norman, Jr., ALPA, National Airlines
Capt. W. R. Sonneman, Trans World Airlines

Full Trial

Capt. R. K. Booth, Continental Air Lines
Capt. Wilfred M. Carlton, Western Air Lines
Capt. D. L. Carter, Western Air Lines
Capt. Bill Connor, Delta Air Lines
Capt. H. H. Cusanelli, American Airlines
Capt. Terry A. Daniel, USAF
Mr. Ken Erdman, Engineering Test Pilot, FAA
Capt. Jerry T. Frederickson, Northwest Airlines
Capt. E. Craig French, USAF, 3MAS
Mr. James E. Gannett, Boeing Company Flight Test
Capt. Ed Gorman, Continental Air Lines
Capt. Ron Hanna, American Airlines
Capt. Ray Lahr, United Air Lines, ALPA
Capt. Jim R. LeBel, Western Air Lines
Capt. Joe J. Mullins, Continental Air Lines
Maj. Philip G. Nelson, USAF, IFC
Maj. W. Steve Quigley, USAF, MAC
Capt. Paul F. Rathert, Western Air Lines
Capt. R. W. Reichardt, Continental Air Lines
Capt. Donald E. Riggs, Flying Tiger Line
Capt. Les Spreen, American Airlines
Capt. Ted Thompson, USAF, AFISC
Dr. Joe Tymczyszyn, Jr., FAA Flight Standards Service
Capt. Warren Weinstein, American Airlines
Mr. Leon C. Whallon, FAA Aircraft Evaluation Group
Capt. Gordon L. Witter, American Airlines

II METHOD

This section describes the manner in which the DC-10 simulation was configured for the advanced tests and provides an overview of the evaluation plan adopted for testing the experimental aiding concepts. More detailed descriptions of the aiding concepts tested and the experimental designs adopted for each phase of testing are presented in subsequent sections.

A. Simulator Configuration

1. Simulator Cab/and Motion Base

The Douglas MBDFS shown in Figure 1 consists of a modified DC-10 cockpit mounted on a six-degree-of-freedom motion base. A Redifon visual system is used to represent the external visual scene. Programs for data acquisition and DC-10 equations of motion were mechanized on a Sigma-5 hybrid computer. The simulation was modified to include specified windshear and turbulence models. Cockpit instrument panels were reconfigured to include the experimental displays.

The modified DC-10 cockpit contained Captain, First Officer, and Instructor stations. The Instructor station, located aft of the Captain's station, was equipped for selection of test conditions, and control of mission start, reset, and position freeze. Subject pilots flew simulated approach sequences from the Captain's station with the basic configuration shown in Figure 2. All flight controls, flight instruments, guidance systems, and aircraft subsystems necessary for the performance of this study were provided at the Captain and First Officer stations. Except for experimental displays, installed cockpit equipment conformed with standard DC-10 aircraft equipment.

The Sigma-5 computer provided program control of data collection and of simulated aerodynamic response, winds, and turbulence, with appropriate parameter values obtained from lookup tables. Wind profiles

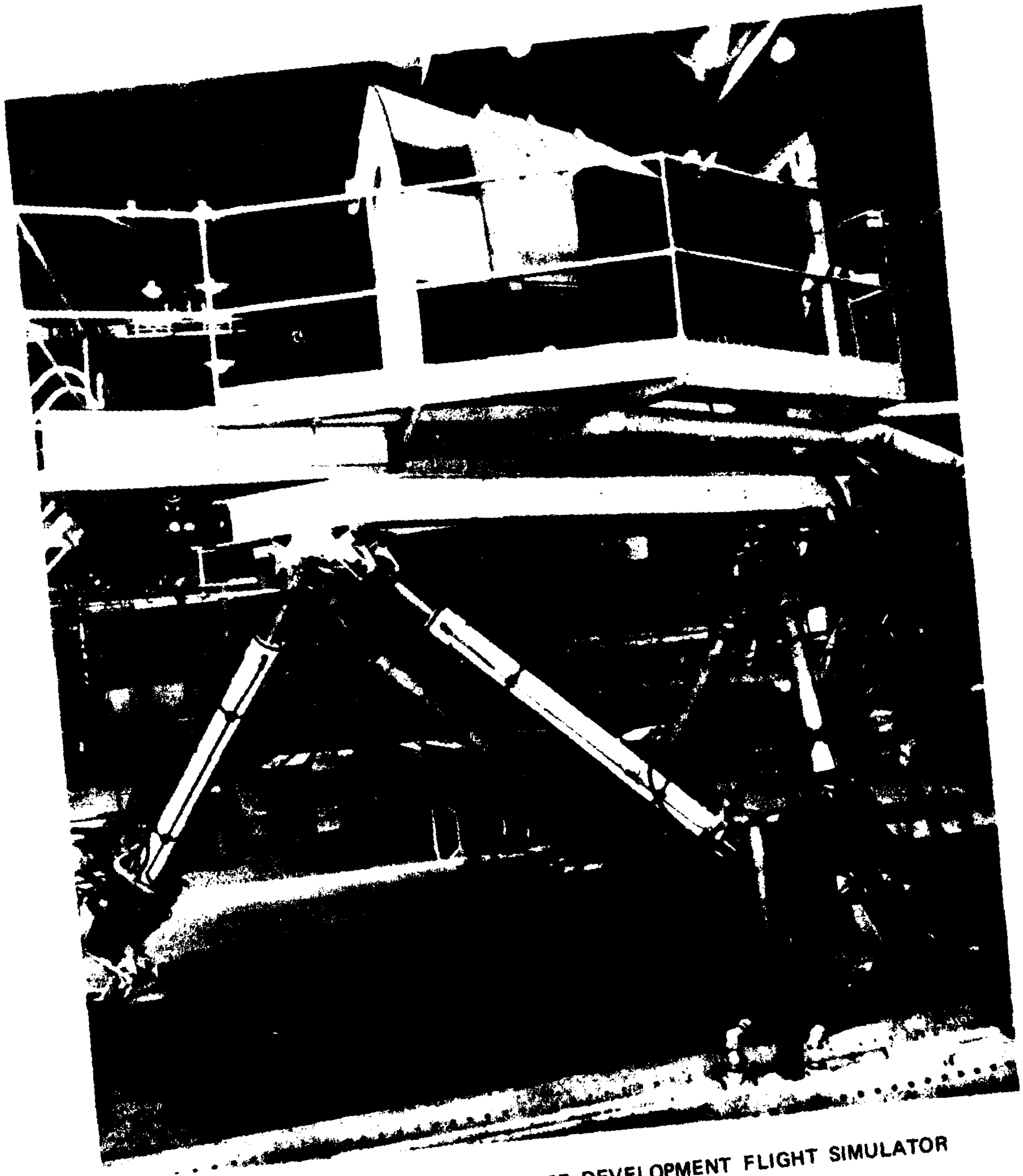


FIGURE 1 DOUGLAS MOVING BASE DEVELOPMENT FLIGHT SIMULATOR

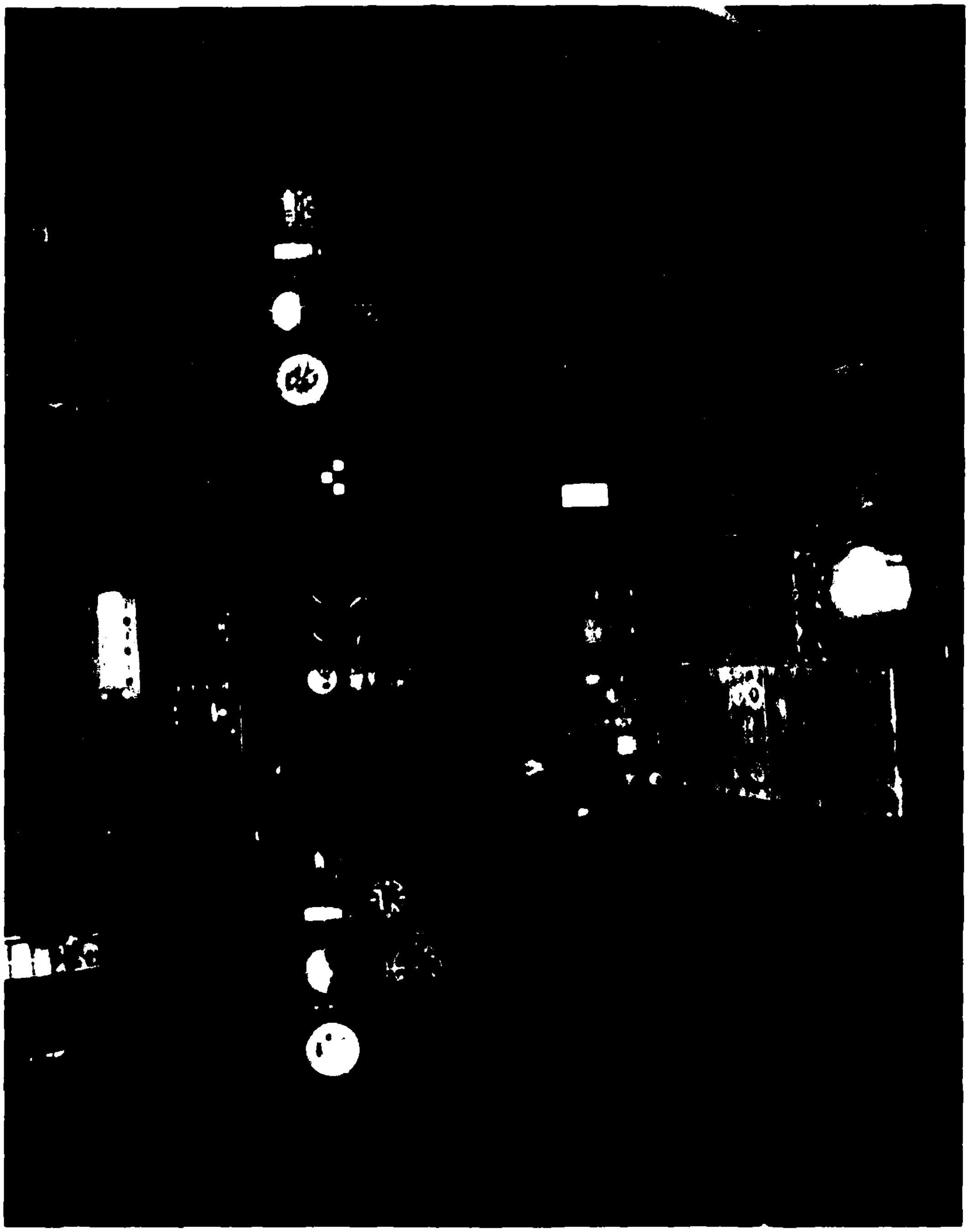


FIGURE 2 SIMULATED DC-10 COCKPIT

and turbulence conditions represented in the simulation were recorded during each simulator run, and at the end of each run a "quick look" summary was provided.

The external visual scene was generated by a Redifon rigid model system with a scale factor of 750 to 1. The visual scene is represented by a 620-line color television image, and is displayed by high-resolution monitors viewed through a special Douglas Aircraft asymmetric lens. The Captain and First Officer stations are each equipped with a separate monitor and lens. The visual system has a maximum approach distance of 2.25 miles and an eye altitude range of 725 feet to 15 feet. Approach and strobe lighting were realistically simulated under variable ceiling and runway visual range (RVR) conditions.

The simulator has six degrees of freedom, provided by a six-jack (Franklin Institute) motion base. Motion is controlled from a ground control station located adjacent to the cockpit/platform. Motion capability is summarized in Table 2.

Table 2

SIMULATOR MOTION LIMITS

AXIS	EXCURSION	VELOCITY PAYLOAD 20,000 lb	VELOCITY PAYLOAD 3600 lb	ACCELERATION PAYLOAD 20,000 lb	ACCELERATION PAYLOAD 3600 lb
Heave	±42 in.	±39 in./s	±40.5 in./s	±1.65 g	±1.65 g
Sway	±67.5 in.	±67 in./s	±72.3 in./s	±1.43 g	±2.25 g
Surge	±65 in.	±71 in./s	±71.6 in./s	±1.50 g	±2.6 g
Roll	±30.7°	±35.6°/s	±36.2°/s	±7.8 rad/s^2	±7.8 rad/s^2
Pitch	±33.3°	±33.6°/s	±32.0°/s	±7.8 rad/s^2	±7.8 rad/s^2
Yaw	±38.7°	±36.3°/s	±40.3°/s	±7.9 rad/s^2	±7.8 rad/s^2

2. Aircraft and Runway Simulation

Equations of motion for the DC-10 series aircraft provided continuous flight simulation over the low-speed flight envelope. A landing gross weight of 350,000 lb was used in the calculations. Normal flap

extension on the approach was 50 degrees. Table lookup functions were used for nonlinear aerodynamic data such as lift and pitching moments. Ground effects on aerodynamic coefficients were simulated over the entire flap range. Nonlinear lateral control spoilers were included. Control surfaces were simulated as either first- or second-order systems, with dead zones and position limits included for all surfaces.

Simulated approach and landing scenarios were designed to represent a manually flown ILS flight-director approach under Category I weather conditions, with a transition to external visual reference for the landing maneuver. Cloud cover was simulated down to a breakout altitude of 150 feet above runway elevation, with visual conditions after breakout representative of 3000 feet RVR. The simulated runway was 150 feet wide and 7000 feet long, at sea level, with guidance corresponding to a Category II ILS with a 3 degree glide slope. The ILS simulation included beam bends from a table lookup and beam noise.

B. Wind Profiles for Simulation Tests

Wind profiles selected for use in the simulator tests represent three broad classes of meteorological conditions commonly recognized as significant producers of low-level wind shear:

(1) Atmospheric boundary conditions
(2) Frontal systems
(3) Thunderstorms

To select specific wind profiles we performed a computer model analysis of aircraft responses to various wind shear conditions. Wind data from tower measurements, accident reconstructions, and meteorological math models were converted to a three-dimensional wind field programmed as a function of altitude and longitudinal position. A number of different wind profiles were produced from each wind field by varying the runway position relative to each wind field and, where applicable, the wind model parameterization. Potentially hazardous wind profiles were identified and sorted into three levels of severity by observing the responses of a fast-time computer model of the DC-10 piloted by an ideal-

ized controller algorithm. Twelve wind profiles (four from each severity level) were selected for the piloted simulator tests.

Plots of the wind profiles used in the simulator tests, a detailed description of their implementation, and a description of the turbulence model are given in Appendix A.

C. Evaluation Plan

1. Test Objectives and Approach

Advanced testing of improved ground speed (GNS) and modified flight director (MFD) aiding concepts was carried out in two stages. The first stage, referred to as the Initial Trial, consisted of a series of test exercises designed to evaluate alternative display concepts and computational algorithms for implementing the GNS and MFD techniques, and to determine the need for augmenting these techniques with go-around guidance. The objective of the first stage of testing was to select recommended versions of each technique for evaluation in a second stage of testing, the Full Trial. The objective of the second stage of testing was to determine the level of operational performance and pilot acceptance that may be attributed to the use of the selected techniques in a representative set of wind shear environments.

As a secondary test objective, the need for pilot aiding in coping with low-level wind shear during takeoff and climbout was examined. Several wind shear profiles were designed specifically for evaluating the hazard represented by an encounter during takeoff operations under baseline conditions.

Initial testing consisted of comparative evaluations of four versions of the GNS concept, two versions of the MFD concept, and two proposed instruments for supporting the pilot's decision to continue the approach or go-around. Three separate test exercises were conducted to evaluate the effectiveness and pilot acceptance of these aiding concept alternatives.

Alternative implementations for the GNS concept represent important differences in requirements for cockpit display and airborne

computation. The simplest version tested is simply a digital readout of ground speed. The second version provided guidance on the existing Fast/Slow indicator on the attitude-director indicator (ADI) for maintaining pre-planned ground speed, but did not include a separate display of ground speed. A third version was the two-pointer airspeed/ground speed display (evaluated in earlier simulation tests), augmented by adding the Fast/Slow feature just described. Finally a combination of the digital ground speed display with the modified Fast/Slow indicator was tested.

Alternative test versions of the MFD concept are distinguished by two different ways of adding thrust commands to the modified pitch and roll steering commands tested in earlier studies. The thrust commands were presented on the standard Fast/Slow indicator on the ADI. One version (MFDT-1) provided for speed control based only on acceleration augmentation. The other version (MFDT-2) incorporated ground speed information to compensate for diminishing headwind shears.

The need for go-around guidance was examined by comparing the pilot's ability to detect and respond to unsafe conditions using baseline instruments with his performance on the same task using two new aiding concepts. The first concept was a cockpit display of energy rate developed by Douglas. The second, developed by the FAA, was a cockpit display of aircraft acceleration margin. These instrumentation concepts are discussed in greater detail in Section III.

Initial testing was limited to eight days of simulator utilization time and was carried out using selected evaluation pilots rather than subject pilots. Evaluation pilots were supplied by the FAA, with SRI assistance, and included pilots who had participated as subjects in earlier simulation tests.

After a two-week period for assessing the results of initial testing and for making final adjustments to computational algorithms, selected versions of the GNS, MFD, and go-around guidance techniques were combined into three instrumentation configurations and tested using a larger number of subject pilots. Twenty-six pilots were recruited for this full-scale testing and their performance was considered to be representative

of currently active line pilots operating wide-body aircraft. The basic intent of this test exercise was to develop reliable estimates of the level of operational performance and pilot acceptance that could be expected when the selected aiding concepts are used in the kinds of wind shear environments represented by the test shear profiles.

The basic plan for this Full Trial was to provide the subject pilots with a training session on the use of each aiding concept and then to take test data on their response to four selected wind shear profiles. The four test profiles included severe thunderstorm and frontal shear conditions that were expected to result in missed approaches, and two less severe shears that were considered demanding but negotiable by most pilots. Training runs were designed to assure that pilots were thoroughly familiar with the simulation and the assigned aiding concepts. The wind shear profiles used during training runs were similar to the test profiles.

2. General Test Procedures

Test procedures followed the same general pattern as that established for earlier simulation studies. Pilots were scheduled in pairs and alternated sessions in the simulator. A master run schedule listing the sessions to be completed by each pilot for each scheduled day of simulator utilization was prepared for each test exercise. A standardized project orientation briefing, covering study objectives and the pilot's role in the tests, was presented on the first day. Immediately prior to each scheduled session, pilots were briefed on the assigned aiding concepts and the procedure to be followed in the simulator. Debriefing sessions were conducted immediately following each simulator session to record pilot assessments of the test concepts.

In general, pilots were briefed to conduct each approach as they would in actual line operations and to make approach continuation/go-around decisions on the basis of their usual assessments of the ongoing flight situation. In the GNS and MFD experiments during initial testing, pilots were briefed to initiate a go-around at their discretion, using the same approach acceptance criteria and judgments as they would

in actual flight situations. Note that this is a departure from our earlier wind shear simulation exercises that called for the approach to be continued to 100 feet, with an announcement of go-around decisions above that altitude. In the initial go-around guidance experiment and in the full-scale tests, pilots were briefed to consider the different forms of go-around guidance as advisory information and to initiate a go-around when called for unless they were confident that the approach could be completed within limits and therefore elected to continue.

3. Data Acquisition and Recording

As the approach sequences were executed, 34 flight situation parameters were continuously sampled and recorded on magnetic tape. In addition to this programmed acquisition and storage of digital data, 16 channels of analog data output were recorded on two strip-chart recorders. A detailed description of on-site data recording activity and a listing of the parameters sampled is given in Appendix B.

At the end of each simulator run, a summary data printout was compiled by the computer and was immediately available to on-site test personnel at the line printer. The data content and format of this printout are illustrated in the sample printout reproduced in Figure 3. Elements of the summary data printout indicate the principal types of flight situation data recorded on magnetic tape and include most of the performance measures used to assess the effectiveness of the aiding concept.

The top section of the printout identifies the run, the subject pilot, the test conditions, and the appropriate airspeed V_{REF} and V_{APP} and ground speed GNS_{REF} references for the approach. In the data matrix just below this header information, the values of designated flight situation parameters (column headings) are recorded at various glide slope heights (GS ALT) and at go-around initiation (G/A) or touchdown (TD). Statistics computed over the 500 to 100 foot approach segment are then listed to indicate the accuracy of flight path following, the effectiveness of pilot attempts to control airspeed and ground speed drops below reference values, pilot following of pitch and roll steering commands, and indications of primary flight control activity. More detailed descriptions of these data elements are also given in Appendix B.

AALS TASK 2, PHASE 3 SIMULATOR DATA

DATE:	10-05-77	SUBJECT:	03	V(REF):	136. KT
TIME:	10:57:16	DISPLAY:	6	V(APP):	146. KT
RUN NO:	23065	WIND PRO:	1	GNS(REF):	115. KT
RUN VL:	1	REP	C		

GS ALT (FT)	DIST (NM)	VERT OFFSET (FT)	LAT OFFSET (FT)	VERT SPEED (FPS)	LAT SPEED (FPS)	GROUND SPEED (KT)	AIR SPEED (KT)	LIMIT (1=T)	ENERGY RATE	ACCEL MARGIN	ALT (FT)
8CC	-2.51	19.	-25.	-12.1	-1.8	116.	162.	1	-203.	2.5	819.
5CC	-1.57	-4.	-32.	-9.4	-2.2	115.	160.	1	-204.	2.4	496.
2CO	-.63	9.	-4.	-18.6	-1.2	120.	156.	1	-546.	-.1	209.
1CC	-.31	5.	-24.	-15.6	-4.7	129.	162.	1	-153.	-1.0	105.
TC	-.09	-7.	-24.	-7.9	5.3	132.	145.	1	-380.	2.0	20.
G/A	.0C	C.	C.	.0	.C	C.	0.	0	0.	.0	0.
EDL	.00	C.	C.	.0	.C	C.	C.	C	0.	.0	0.
DAL	-.63	11.	-4.	-18.2	-1.1	12C.	156.	C	-410.	-.0	213.

TD THE = 5.0 PHI = -2.5 GNS ERROR = 10.5

OVER THE 50C FT. TO 10C FT. FLIGHT PATH SEGMENT:

	RMS	MAX	MIN
AIRSPEED ERROR (KT)	12.9	19.7	7.4
GNS ERROR (KT)	3.1	10.5	-.5
G/S DEV (DOTS)	.4	.9	-.7
LOC DEV (DOTS)	.1	.2	.0
VERT OFFSET (FT)	14.8	20.7	-29.7
LAT OFFSET (FT)	26.2	-3.1	-37.9
PITCH STR. (BW)	1.5	4.0	-2.6
ROLL STR. (BW)	1.2	2.5	-3.2
ELEVATOR (DEG)	3.6	9.1	-3.8
AILERON (DEG)	4.2	9.7	-6.1
ENERGY RATE	387.5	.0	-681.3
ACCEL. MARGIN	1.9	3.2	-1.1

FIGURE 3 SAMPLE SUMMARY DATA PRINTOUT

III INITIAL TRIALS

This section describes the pilot aiding concepts tested in the initial series of simulation exercises and presents the test results. The organization of this discussion follows the breakdown of initial testing into three separate experiments. Four alternative implementations of the groundspeed (GNS) concept were evaluated in the first experiment, two versions of the modified flight director (MFD) were tested in the second experiment, and the third experiment examined the relative effectiveness of three ways of augmenting the GNS and MFD techniques with go-around guidance.

A. Groundspeed Concepts

1. Alternative Implementations

The four versions of the ground speed concept selected for testing represent alternative cockpit display arrangements for supporting the "minimum pre-planned groundspeed" technique evaluated in earlier simulation studies. This technique calls for the pilot to manage his airspeed during the approach so that groundspeed does not drop below a preselected reference value. The reference groundspeed is a pilot-selected target speed for touchdown and is derived by converting the nominal approach speed for a no-wind condition (V_{REF}) to true airspeed and then subtracting the reported surface headwind component. The four alternative display arrangements were defined as follows:

a. Integrated Airspeed/Groundspeed Display plus Modified Fast/Slow Speed Command (GNS-3)

This display arrangement is illustrated in Figure 4. A second pointer is added to the conventional airspeed indicator to provide groundspeed information and an additional reminder bug is provided for the pilot to manually set the groundspeed reference. The display of groundspeed information is thus the same as in the two-pointer concept

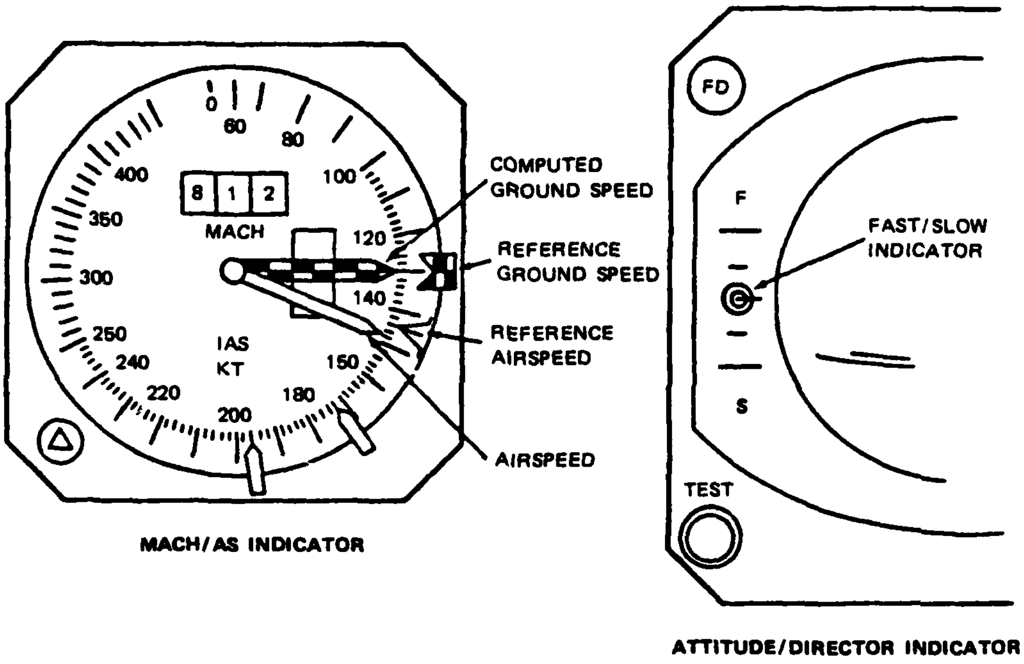


FIGURE 4 AIRSPEED/GROUNDSPEED DISPLAY WITH FAST/SLOW

tested in Phase 2 (GNS-2) and the computational algorithm for the groundspeed element is the same. However, in this test display, the striped pointer normally used to indicate maximum allowable airspeed (V_{mo}) is used for groundspeed and the groundspeed reminder bug is shape coded for better distinguishability.

In the display arrangement shown (designated as GNS-3), the drive signal for the Fast/Slow indicator on the ADI has been modified to incorporate groundspeed "error" as well as the conventional airspeed deviations from pilot-selected approach speeds (V_{APP}). The modified computational algorithm for the speed command is given in Figure 5. Computed airspeed (IAS) and groundspeed (GNS) are filtered, as shown, and summed with their respective reference values. The speed command displayed is the "minimum" value of the two speed deviations, limited to ± 20 kt on the indicator.

The effect of this speed command algorithm, when the pilot maintains the null indication, is to keep both airspeed and groundspeed at or above selected references. Airspeeds higher than V_{APP} may be required to maintain GNS_{REF} with a headwind on approach; with a tailwind, airspeed will not be allowed to drop below V_{APP} and groundspeeds well above GNS_{REF} may be indicated. In any case, pilot cross-check of the IAS/GNS indicator would show, at a glance, which speed deviation was driving the Fast/Slow indicator.

b. Modified Speed Command only (GNS-4)

For this version of the GNS concept, only the modified Fast/Slow speed command is available to the pilot and groundspeed is not displayed. The computational algorithm for the speed command is as shown in Figure 5.

c. Digital Groundspeed Readout (GNS-5)

This display concept is simply a digital readout of computed groundspeed located above the ADI, as shown in Figure 6. When this display condition was selected, the Fast/Slow speed command operated in the conventional manner to indicate deviations from pilot-selected (or

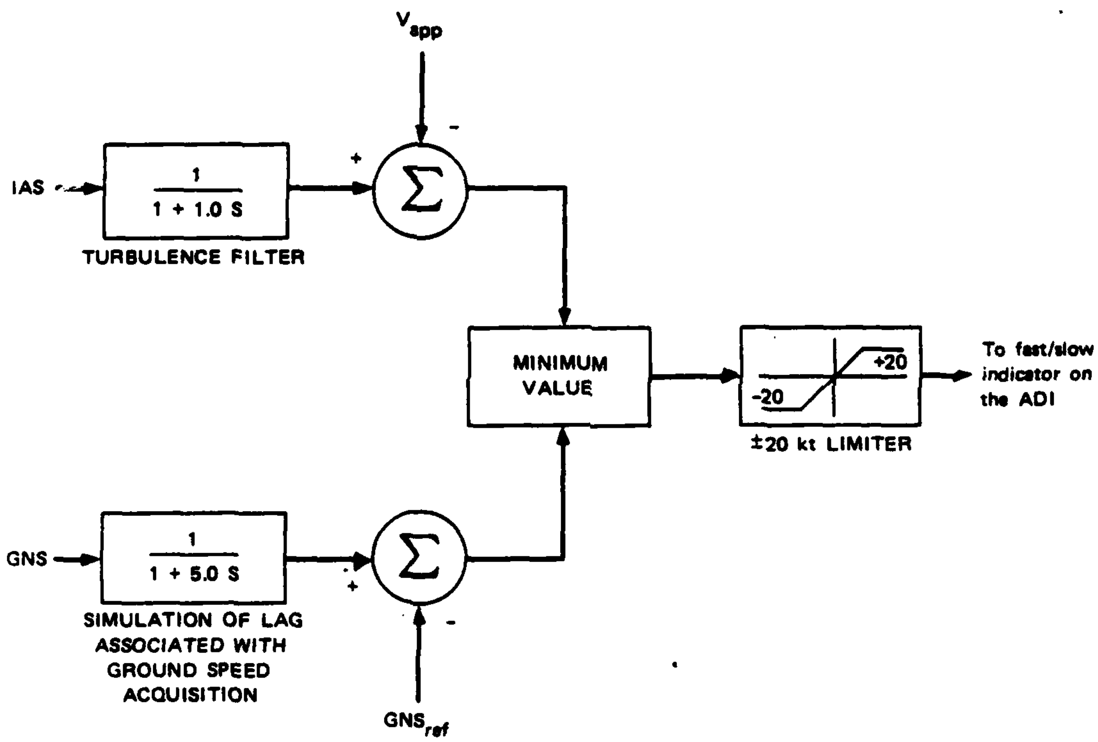


FIGURE 5 COMPUTATIONAL ALGORITHM FOR DERIVING THE MODIFIED FAST/SLOW SPEED COMMAND

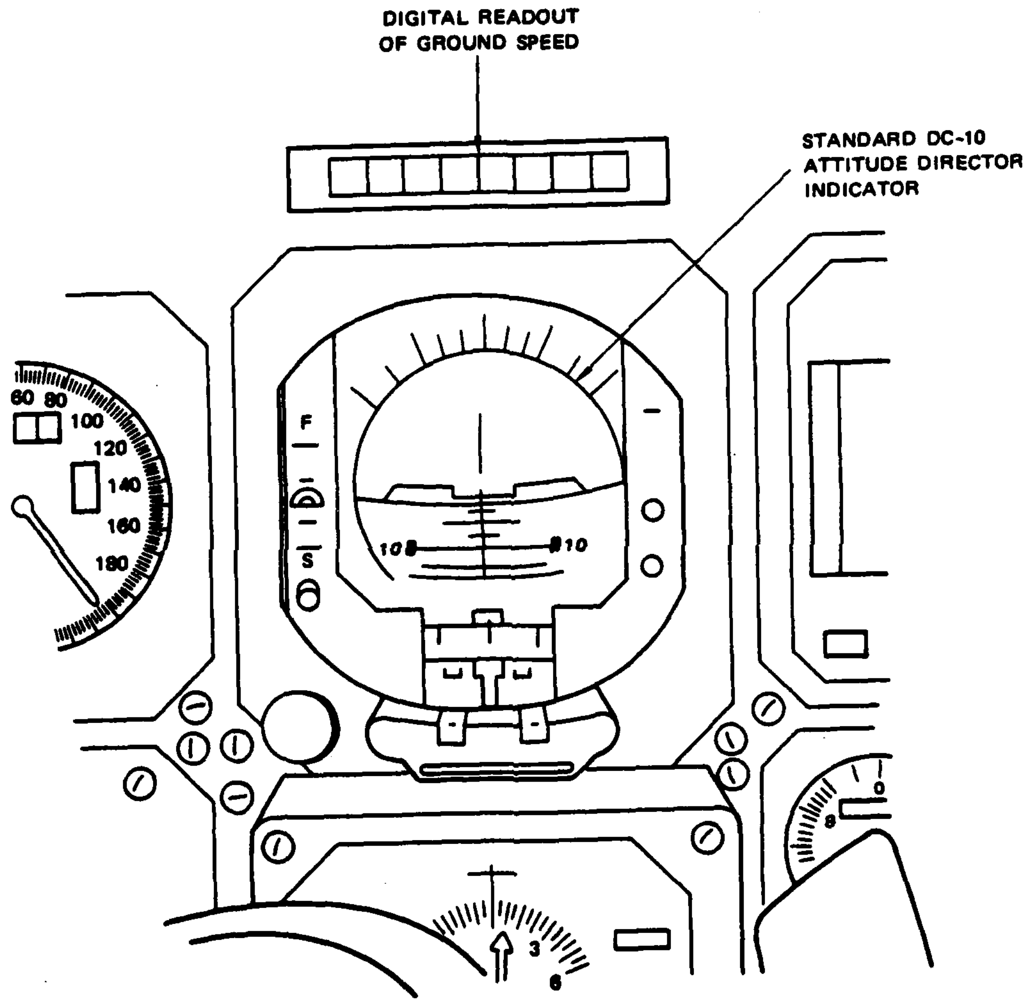


FIGURE 6 DIGITAL READOUT OF GROUNDSPEED

computed) target approach speeds. Pilots were briefed to follow the same technique of using GNS_{REF} as an additional minimum approach speed and a conventional airspeed reminder bug (not shape coded or painted to match the GNS pointer) could be set to indicate GNS_{REF}.

d. Digital Groundspeed Readout with Modified Speed Command (GNS-6)

This display is the same as GNS-3 except that the digital readout just described, rather than the second pointer on the airspeed indicator is used to provide groundspeed information.

2. Test Plan

The design adopted for the first experiment is shown in Table 3 and calls for each of the four evaluation pilots to fly six data runs using each of the alternative GNS concepts. The order of pilot exposure to the different concepts was partially counter-balanced to preclude any systematic bias in the data due to carry-over effects. Data runs were flown against six wind profiles selected from the set described in Section II to include 3 high severity and 3 moderate severity shear conditions. The same six profiles were applied to each alternative GNS concept using a varying pattern of exposure.

The experimental design provided data on a total of 96 approach sequences (runs), allowing contrasts among the alternative GNS concepts to be based on 24 runs. A single session in the simulator consisted of 12 data runs, covering two versions of the aiding concept plus additional runs for training. The full run schedule was thus completed in 8 sessions, with 2 sessions required for each pilot. Table 4 shows the order in which each pilot was assigned to the alternative GNS concepts to control for carry-over effects. The order in which pilots were exposed to the six wind profiles within a scheduled simulator session was scrambled so that pilots could not learn the sequence and thus anticipate the character of the shear encounter.

Table 3

EXPERIMENTAL DESIGN FOR THE GROUNDSPEED EXPERIMENT

Evaluation Pilot	Alternative GNS Concepts: GNS-3	GNS-4	GNS-5	GNS-6	Σ
1	6	6	6	6	24
2	6	6	6	6	24
3	6	6	6	6	24
4	6	6	6	6	24
	24	24	24	24	96

Data obtained in this experiment were intended to guide the selection of groundspeed displays for more in-depth evaluation in the full-scale tests. The selection was to be based on both system performance measures (approach and landing outcomes) and pilot evaluations, with relatively greater weight given to the latter. Three of the evaluation pilots had prior experience with the groundspeed display concepts in earlier simulation studies of low-level wind shear and the fourth was a Douglas engineering test pilot.

Table 4

ORDER OF PILOT ASSIGNMENT TO
ALTERNATIVE GROUNDSPEED CONCEPTS

Evaluation Pilot	Simulator Session: 1st	2nd
1	GNS-3/GNS-4	GNS-5/GNS-6
2	GNS-5/GNS-3	GNS-6/GNS-4
3	GNS/6/GNS-5	GNS-4/GNS-3
4	GNS-4/GNS-6	GNS-3/GNS-5

3. Test Results

The relative effectiveness of the alternative groundspeed display concepts in the simulated shear encounter is summarized in Table 5. Recorded flight situation data were used to determine whether the aircraft was within operationally acceptable limits at the Inner Marker and at touchdown and these counts are given in the table as criterion measures 1 and 2. Limiting values for this assessment are listed in Table 6 for the Inner Marker and in Table 7 for touchdown. The number of go-arounds and crashes (touchdown off the runway) is also given for each display concept.

On both touchdown performance and the "Safe Outcome Index," which gives credit for a safe execution of a missed approach, the best approach and landing performance was obtained using the GNS-3 and GNS-5 display concepts. Differences between the alternative display arrangements were slight at the Inner Marker. However, more out-of-limit approaches were converted to within-limit landings when the GNS-3 and GNS-5 displays were used. It is interesting to note that approach and landing outcomes were better using the digital display of groundspeed alone (GNS-5) than with display concepts incorporating the modified Fast/Slow speed command.

In the debriefing sessions following their exposure to the aiding concepts in the simulator, the evaluation pilots were asked to critique the alternative display arrangements and to indicate the one they felt would be most acceptable for line operations. Pilot preferences were clearly in favor of the two-pointer display of groundspeed with the modified Fast/Slow indicator (GNS-3). Only one pilot (with no prior experience with the display) felt that the use of the second speed minimum (GNS_{REF}) might produce some confusion in cross-checking between the Fast/Slow and airspeed indications. The general reaction, as in earlier studies, was that the two-pointer display provided the best information on the winds affecting the aircraft and for estimating the potential wind shear.

Table 5

SUMMARY OF APPROACH AND LANDING OUTCOMES
IN THE INITIAL TESTING OF GROUNDSPEED DISPLAY CONCEPTS

Criterion Measure	Display Concept GNS-3	GNS-4	GNS-5	GNS-6
1. Number of Approaches Completed Within Limits	9	10	12	12
2. Number of Landings Completed Within Limits	19	13	22	14
3. Number of Successful Go-Arounds	5	5	1	3
4. Number of Crashes	0	1	0	1
5. Safe Outcome Index[a]	100%	78%	96%	71%

[a]Percentage of total data runs against all shear conditions (n = 24) resulting in a within-limits touchdown or successful go-around.

Table 6

INNER-MARKER LIMITS

Vertical deviation from glide slope: ± 28 ft (i.e., ± 0.8 deg, ± 200 μamp, ± 3.3 dots or about 0.8 dots over full scale)
Lateral deviation from localizer centerline: ± 75 ft (i.e., ± 0.54 deg, ± 40 μamp, ± 0.7 dots)
Rate of descent: 25 ft/sec (1550 ft/min)

Table 7

LANDING OUTCOME LIMITS

Touchdown position
Along runway: threshold, 3000 ft
Lateral deviation from centerline: ± 50 ft.
Touchdown velocities
Rate of descent: 11 ft/sec (660 ft/min)
Lateral speed: 15 ft/sec
Touchdown attitude
Pitch angle: +1 to +13 deg
Roll angle magnitude: 9 deg

All of the evaluation pilots found it helpful to have the Fast/Slow command on the ADI so that the speed management task could be accomplished by reference to a single instrument. However, only one of them felt that the Fast/Slow command alone (GNS-4) was adequate; most of them liked having groundspeed information available for cross-checking. The display arrangement ranked in second place was the modified Fast/Slow with the digital groundspeed readout (GNS-6).

There was some tendency for pilots to prefer the digital groundspeed display alone (GNS-5) over the GNS-4 concept, even though most of them felt the mental workload was excessive using the digital display. They were also aware of the conflict between the Fast/Slow indicator, operating in its normal "airspeed error" mode, and the airspeed required to maintain the reference groundspeed. As indicated earlier in this discussion, however, pilot performance of the speed management task was not degraded when the GNS-5 display was used.

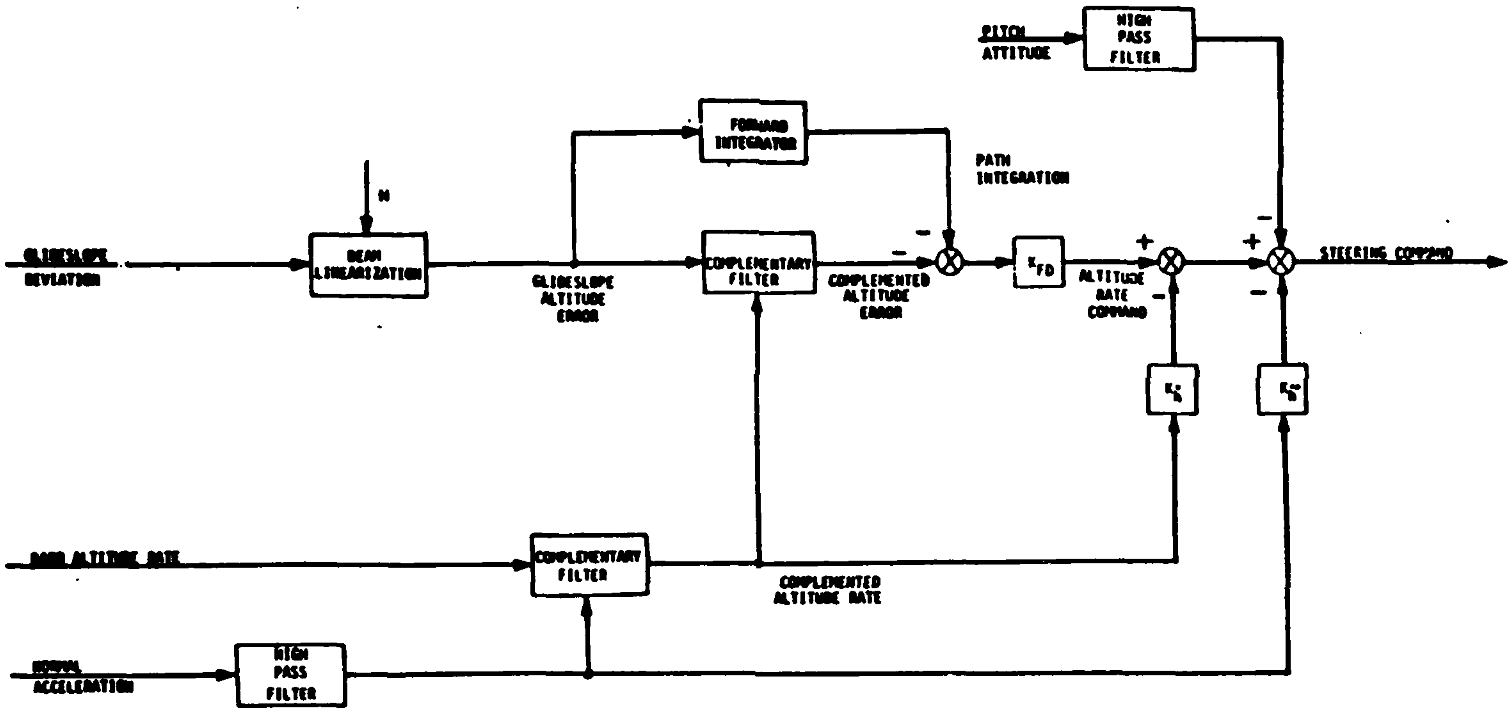
B. Modified Flight Director Concepts

1. Alternative Implementations

Computational algorithms for deriving pitch and roll steering commands in the modified flight director (MFD) were the same for both of the versions tested in this study. These acceleration-augmented steering commands were based on the control laws developed by Collins for the DC-10 in earlier work.[2] For the reader's convenience, the modified longitudinal and lateral control laws are reproduced in Figure 7. For comparison, simplified block diagrams of the conventional unmodified flight director control laws for the DC-10 are presented in Figure 8.

The distinguishing features of the two verions of the MFD tested in the present study was the addition of a thrust command displayed using the Fast/Slow indicator. In the first version (MFDT-1), this thrust command was derived by adding longitudinal acceleration and using glide slope deviation as a pseudo-prediction of wind shear. The control law for this version of the MFD thrust command is diagrammed in Figure 9.

The second version of the MFD (MFDT-2) used the same control laws for pitch and roll steering and provided a thrust command based on the availability of groundspeed information. A block diagram of this version of the thrust command is given in Figure 10. Computed groundspeed and the headwind component in the touchdown zone (TDZ) are used as shown to bias the speed command to compensate for a diminishing headwind shear.



COLLINS RADIO-ROCKWELL INT'L
4 FEB. 1977

FAA WINDSHEAR PHASE 2
SIMPLIFIED LONGITUDINAL CONTROL LAW

FIGURE 7(a) SIMPLIFIED LONGITUDINAL CONTROL LAW FOR MODIFIED FLIGHT DIRECTOR

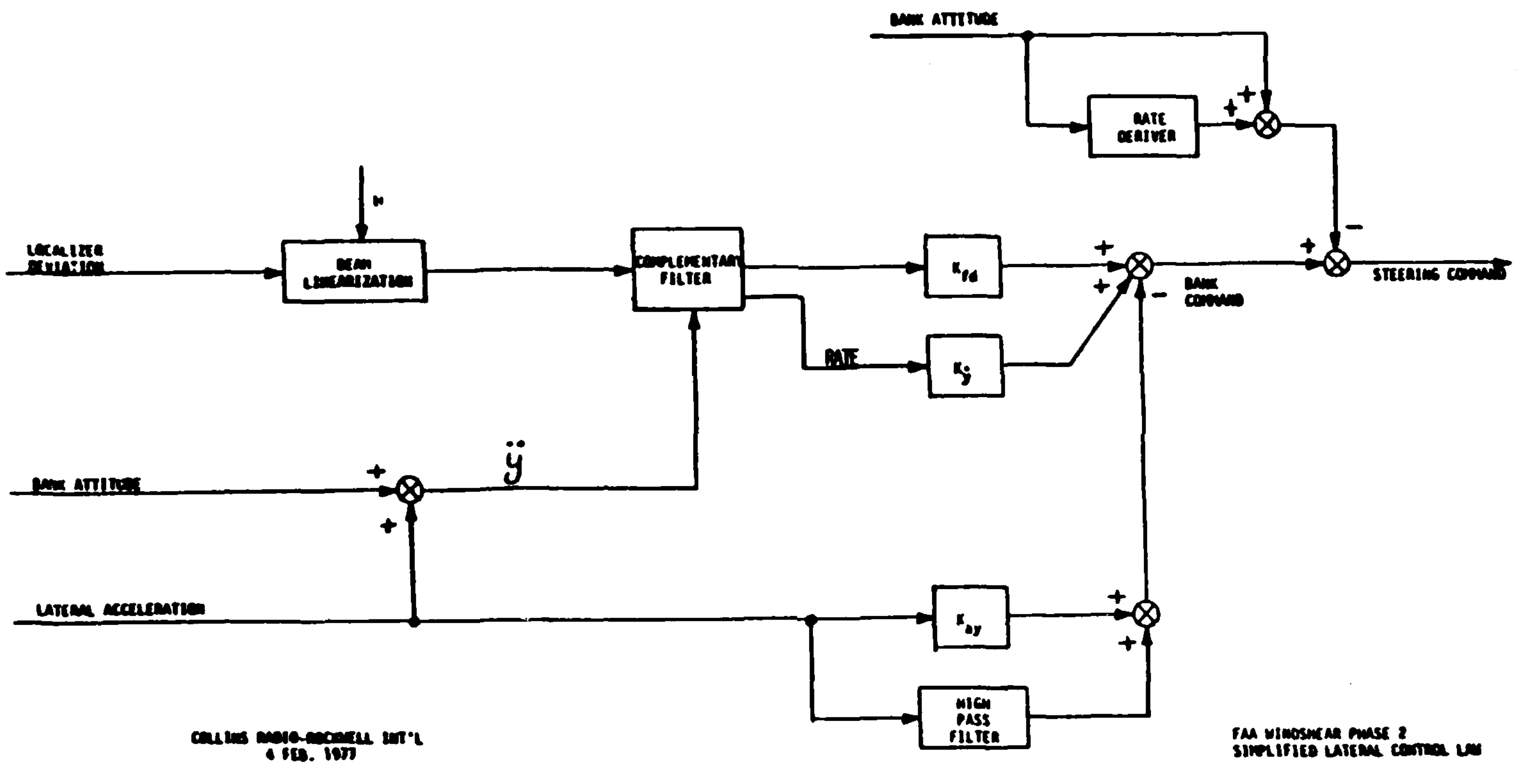


FIGURE 7(b) SIMPLIFIED LATERAL CONTROL LAW FOR MODIFIED FLIGHT DIRECTOR

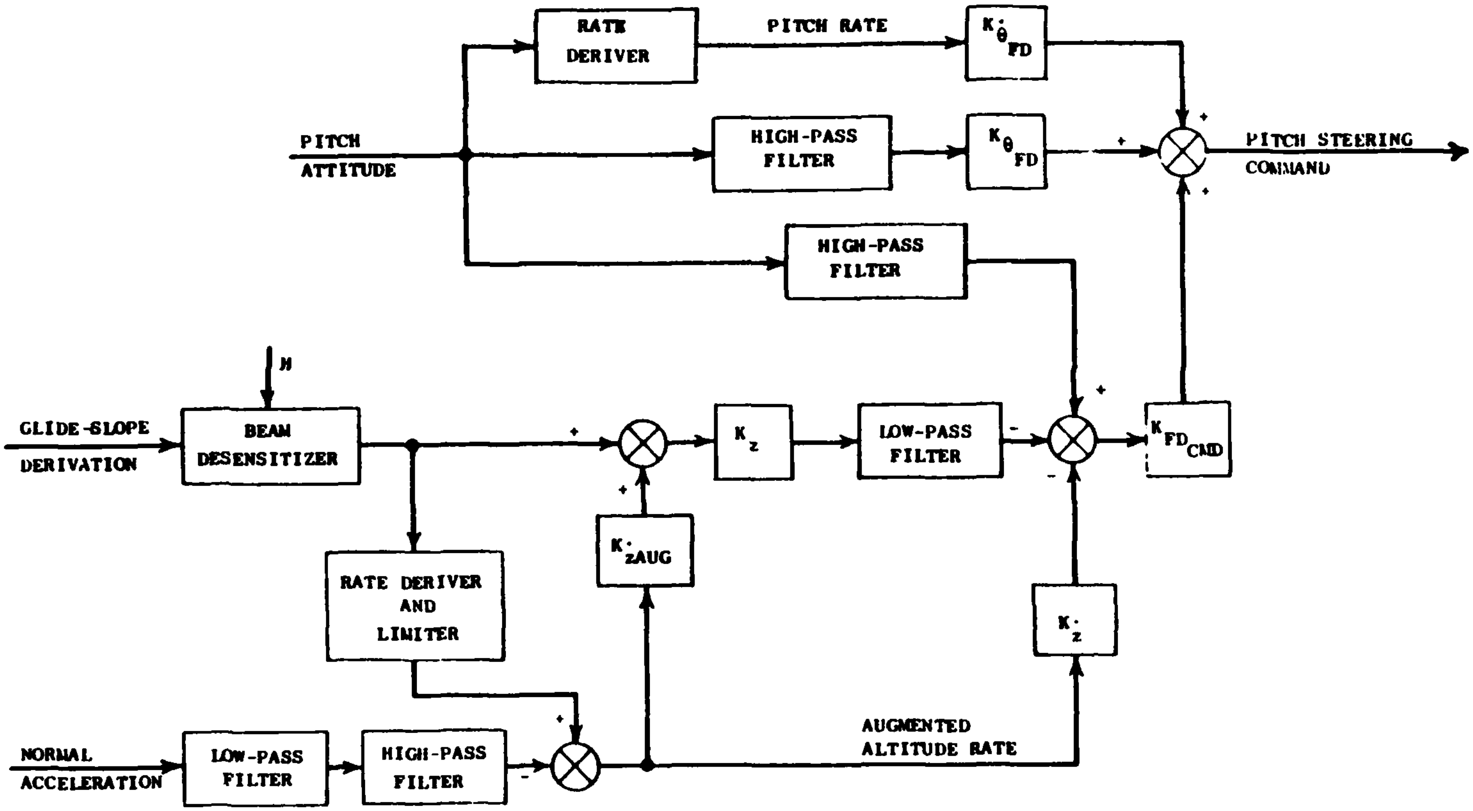


FIGURE 8(a) BASELINE DC-10 FLIGHT DIRECTOR: GLIDE-SLOPE TRACK

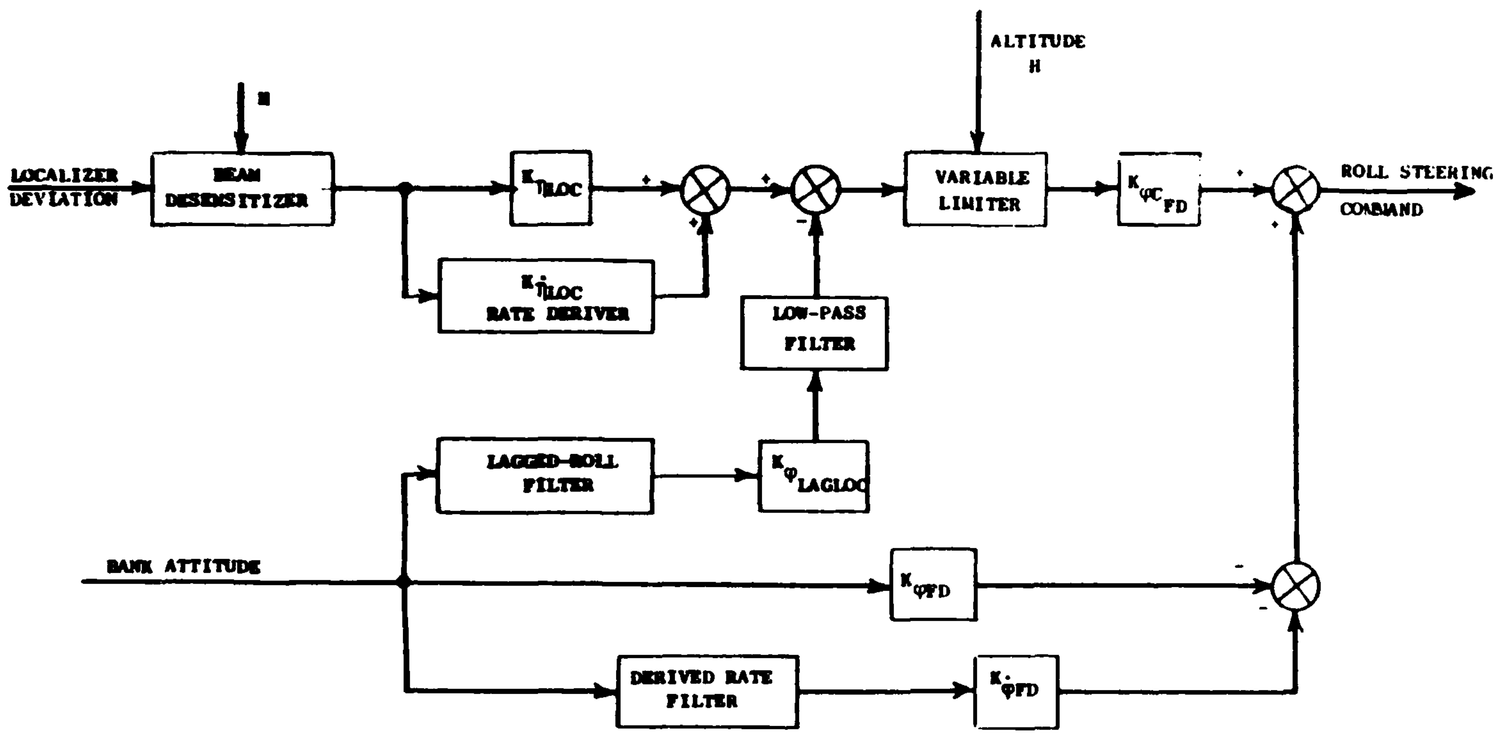


FIGURE 8(b) BASELINE DC-10 FLIGHT DIRECTOR: LOCALIZER TRACK

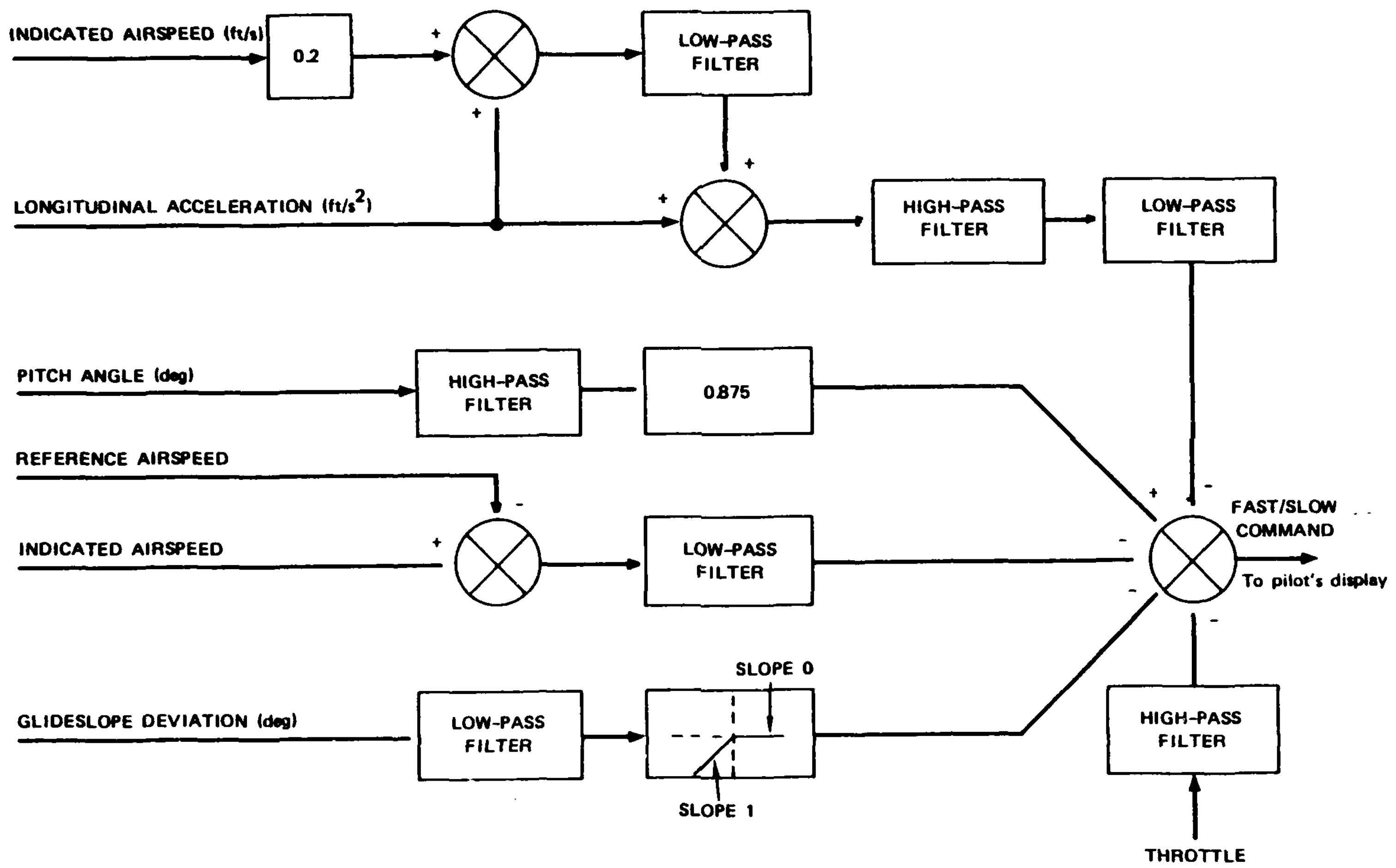


FIGURE 9 MODIFIED SPEED AXIS CONTROL LAW MFDT-1 (Without Groundspeed Information)

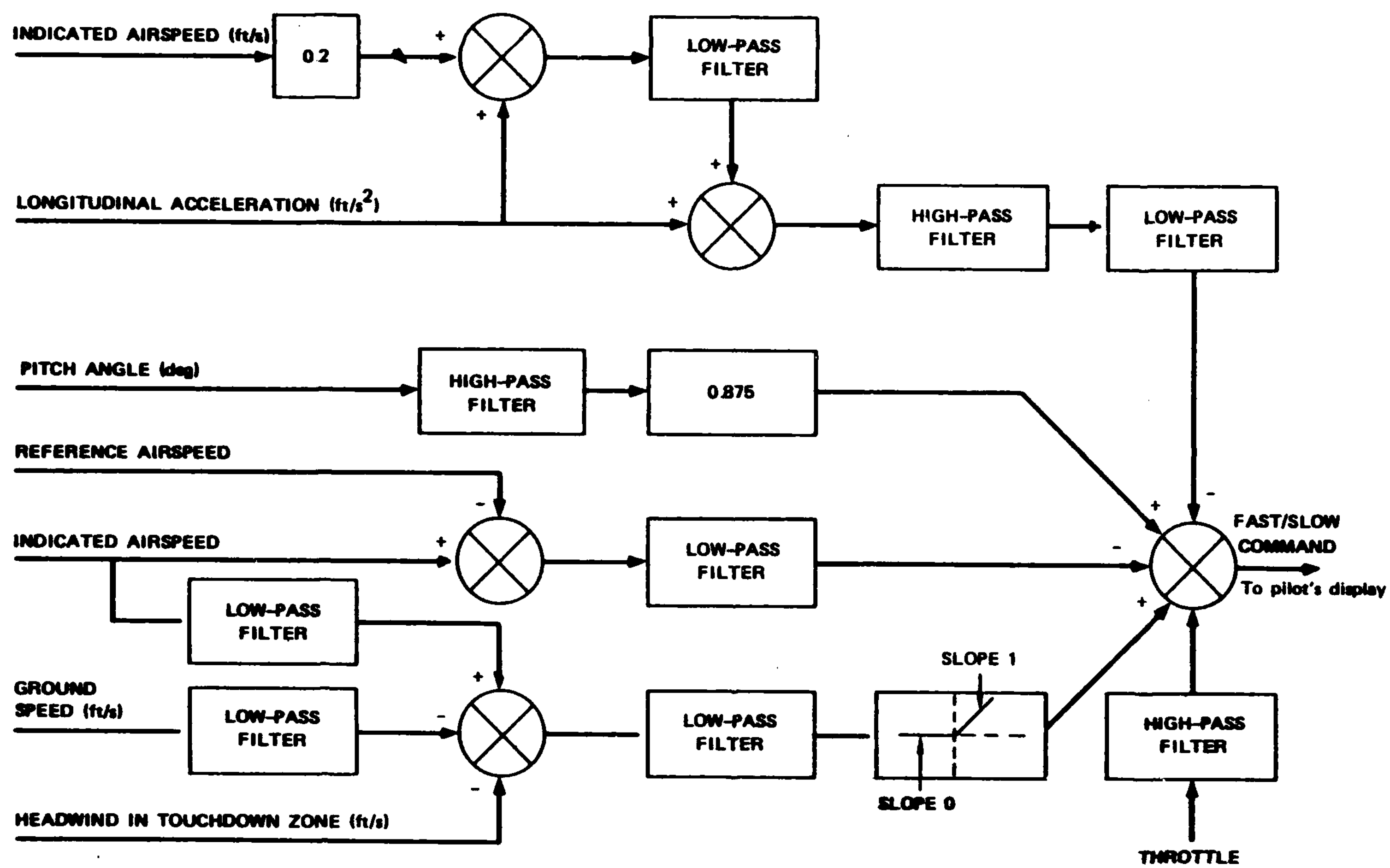


FIGURE 10 MODIFIED SPEED AXIS CONTROL LAW MFDT-2 WITH DIMINISHING HEADWIND SHEAR COMPENSATION

The pilot's task, using either version of the MFD, was to follow the steering commands as closely as he could and to maintain the null position (i.e., no speed error) on the Fast/Slow indicator. Thus, the experimental task did not differ from conventional approach management by flight director reference. However, the effect of the modified flight director control laws was to further quicken both the steering and speed commands and the pilot's task was expected to be more demanding.

2. Test Plan

Four evaluation pilots were also used for the second experiment and a similar evaluation plan was adopted. This plan called for each pilot to fly six data runs using the two alternative MFD concepts (MFDT-1 and MFDT-2). Data runs were flown against six wind profiles, using the same combination of 3 moderate and 3 severe shear conditions. The full run schedule this consisted of 48 runs and contrasts between the two MFD concepts were again based on 24 data runs.

Each pilot completed the run schedule in a single session in the simulator and the experiment was completed in 4 sessions. Table 8 shows the order in which pilots were exposed to the two MFD concepts to control for carry-over effects.

Table 8

ORDER OF PILOT EXPOSURE TO ALTERNATIVE MFD CONCEPTS

Pilot	Concept Ordering
1	MFDT-1 → MFDT-2
2	MFDT-2 → MFDT-1
3	MFDT-1 → MFDT-2
4	MFDT-2 → MFDT-1

The six wind profiles used in this experiment were the same as those selected for the first experiment and the order of pilot exposure was scrambled to preclude learning and sequence effects.

3. Test Results

Summary data on approach and landing outcomes using the two versions of the MFD are presented in Table 9. Criterion measures listed in the first column are the same as those described earlier for the testing of groundspeed display concepts. The numbers presented in Table 8 are based on 24 data runs for each version of the MFD and represent pilot performance on all six of the wind shear conditions.

The data show that the number of within-limit approach and landing outcomes was substantially higher when MFDT-2 was used. This version of the MFD used groundspeed information in the thrust command algorithm to compensate for diminishing headwind shears, but was otherwise the same as MFDT-1. The Safe Outcome Index is also higher for the MFDT-2 version and we may conclude that approach management performance is enhanced by this treatment of the thrust management display.

Table 9

SUMMARY OF APPROACH AND LANDING OUTCOMES

IN THE INITIAL TESTING OF ALTERNATIVE MFD THRUST COMMANDS

Criterion Measure	MFDT-1	MFDT-2
1. Number of Within-Limit Approaches (Inner Marker)	6	13
2. Number of Within-Limit Landings (Touchdown)	11	16
3. Number of Successful Go-Arounds	8	5
4. Number of Crashes	5	3
5. Safe Outcome Index	79%	88%

Pilot evaluations were evenly divided with two pilots preferring each version of the MFD. Differences in the amount of throttle activity required with the two thrust commands were apparent to the pilots, but they didn't agree on the relative merits of the two. All of

the pilots commented on the increased pilot workload on both versions of the MFD and only one (an airline pilot) felt that this would be acceptable for routine line operations.

C. Go-Around Advisory Concepts

1. Alternative Implementations

The third experiment in the initial testing series was designed to determine the additional operational benefits that might be realized if some form of explicit guidance were provided to the pilot to indicate that a go-around should be considered. The three forms of go-around guidance evaluated in this experiment are described below.

a. Modified Baseline Procedure (MBP)

Under this test condition, the pilot conducted a normal flight director approach using conventional (unmodified) DC-10 cockpit instrumentation and following established approach management procedures. This is the condition distinguished as "baseline" in earlier studies. Go-around guidance was added to this condition by a modification to the First Officer's call-out of approach progress. Flight situation monitoring was the same (i.e., altitude, airspeed, sink rate, flight path deviations); the modification consisted of having the First Officer call out "go-around advised" when the aircraft was below 500 ft AGL and the following limits on selected flight situation parameters were exceeded:

(1) Rate-of-descent > 1250 ft/min

(2) Glide slope deviation > 1.75 dots low

b. Acceleration Margin Indicator (ΔA)

The acceleration margin concept was developed by FAA to provide a wind shear alert to the pilot prior to an encounter with severe shear conditions. This concept provides for an index of the aircraft's acceleration capability relative to anticipated wind shear effects and time available to accelerate to be computed, using the following algorithm:

$$\Delta A = KAA - [VWX\ (0,0) - (IAS - GNS)]\dot{h}/h$$

where ΔA = acceleration margin

KAA = a constant representing the longitudinal acceleration capability of the aircraft in level flight. (For the DC-10 with maximum thrust, 350,000 lbs GW, 50^{o} flaps, and gear down, KAA = 1.67 kt/sec.)

VWX(0,0) = longitudinal surface wind component at 20 ft above the glide-path-intercept point on the runway.

IAS = indicated airspeed

GNS = groundspeed

$\dot{h}$ = altitude rate

h = aircraft altitude AGL

The aircraft's "acceleration margin" (ΔA) may thus be interpreted as the difference between its acceleration capability (KAA) and the acceleration required to successfully negotiate an anticipated shear in the altitude remaining. The expression bounded by the square brackets provides a continuous measure of the anticipated shear by comparing winds aloft (IAS - GNS) with reported surface winds [VWX(0,0)]. The term $\dot{h}/h$ reduces to the time it would take the aircraft to descend from its present altitude to the ground. When the value of ΔA goes negative, it indicates that the acceleration required to negotiate the shear exceeds the aircraft's acceleration capability.

A digital display of scaled (x2) values of ΔA was provided on an alphanumeric readout located above the ADI at the evaluation pilot's station (left seat). A repeater display was available to the First Officer, located immediately below the airspeed indicator. The procedure adopted was to have the First Officer monitor the ΔA readout and to advise the pilot to go around when a stable negative reading was observed below 500 feet.

c. Energy Rate Indicator

This concept was developed by the Douglas Aircraft Company and is based on the notion that the effects of wind shear and/or vertical drafts can be usefully expressed as changes in the aircraft's "total energy," kinetic with respect to the air mass plus potential. A computational algorithm was developed to compare actual energy rates

with "normal" energy rates during an approach without shear conditions and a cockpit display was provided to alert the pilot to an unsafe, energy deficient condition.

The Douglas algorithm for energy rate per unit mass (ENR) is:

$$ENR = \left(\frac{\dot{TE}}{m}\right) = V\dot{V} + g\dot{h}$$

where TE = total energy ($\frac{1}{2}\,mV^2 + mgh$)

m = aircraft mass

V = airspeed

$\dot{V}$ = aircraft acceleration with respect to air mass

$\dot{h}$ = altitude rate

g = 32.2 ft/sec^2

The display of a wind shear alert to the pilot was based on a comparison of actual energy rate, derived using the algorithm just described, with a nominal energy rate based on the nominal approach speed and aircraft landing configuration. The indicator used is illustrated in Figure 11. At computed values of ENR $\leq$ 664 ft^2/sec^3 the pointer would remain in the green segment to indicate "normal" energy rates for the approach. ENR values above this level would move the pointer into the yellow segment to alert the pilot and at ENR values $\geq$ 1028 ft^2/sec^3 the pointer would move into the red zone to indicate a potentially hazardous rate of energy loss.

ENR indicators were installed on both sides of the instrument panel, below the airspeed indicator. The procedure adopted was to have the First Officer monitor the indicator and announce a go-around advisory whenever the pointer remained in the red zone for at least one second. At computed ENR values of 750 ft^2/sec^3, a flashing yellow light illuminated to attract the pilot's attention to the ENR indicator.

2. Test Plan

The go-around advisory systems just described were tested both alone and in various combinations with the groundspeed and modified flight

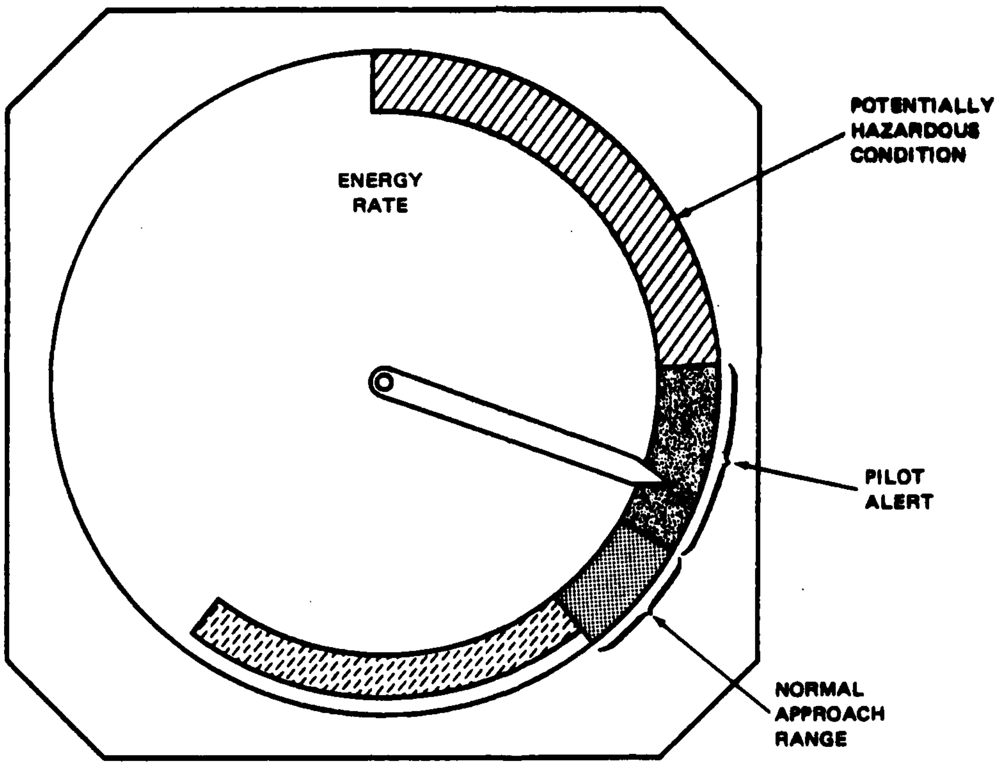


FIGURE 11 DOUGLAS ENERGY RATE INSTRUMENT

director concepts. A baseline (BL) test condition, in which pilots used only conventional instrumentation and their usual approach assessment techniques for deciding whether to continue or go-around, was included for comparison with the experimental concepts. The six test configurations are identified in the column headings of Table 10, which also presents the plan adopted for the experiment.

The ΔA advisory was tested alone and in combination with the best of the groundspeed techniques (GNS-3); the ENR concept was tested alone and in combination with the best modified flight director technique (MFDT-2). It was hypothesized that fewer go-around advisories might be indicated by the ΔA and the ENR displays when they were paired with the experimental approach management techniques rather than the baseline technique.

The evaluation plan shown in Table 10 called for each of the four evaluation pilots to fly six data runs using each alternative aiding configuration. The wind shear profiles used on these data runs were the same as those used in the first two initial tests, but different evaluation pilots were assigned to this experiment. The experimental design provided data on a total of 144 runs and allowed contrasts between alternative aiding configurations to be based on 24 runs. A single session in the simulator consisted of 12 data runs, covering two of the six alternative concepts, plus additional runs for training. The full run schedule was completed in 12 sessions, with each pilot flying 3 sessions. Table 11 shows the order in which pilots were exposed to the six alternative concepts.

3. Test Results

A comprehensive assessment of the relative effectiveness of the go-around advisory concepts was used in this experiment by computing a "Performance Score." A scoring scheme was adopted that considered the severity of the shear encounters. Points were added together for within-limit touchdowns and successful go-arounds, but no points were given for a go-around when the wind shear severity level was moderate. For out-of-limit approaches and crashes, points were subtracted. The Performance

Table 10

PLAN FOR THE GO-AROUND ADVISORY EXPERIMENT

	Alternative Aiding Configuration						
Evaluation Pilot	BL	MBP	ΔA	ENR	ΔA/GNS-3	ENR/MFDT-2	Σ
1	Six data runs using each aiding configuration, flown against 3 moderate and 3 severe wind shear profiles.						36
2							36
3							36
4							36
	24	24	24	24	24	24	144

Table 11

ORDER OF PILOT EXPOSURE TO ALTERNATIVE

GO-AROUND ADVISORY CONCEPTS

	Simulator Session		
Pilot	1st	2nd	3rd
1	BL, ENR	ΔA, ΔA/GNS-3	ENR/MFDT-2, MBP
2	ΔA, ΔA/GNS-3	ENR, BL	MBP, ENR/MFDT-2
3	MBP, ENR	ENR/MFDT-2, ΔA	ΔA/GNS-3, BL
4	ENR/MFDT-2, BL	ΔA/GNS-3, MBP	ΔA, ENR

Score was a ratio of points earned by each aiding configuration to the number of approaches attempted (n = 24). The results are plotted in Figure 12 using separate data points for approach (Inner Marker) and landing (touchdown) outcomes. The ΔA and ENR concepts show substantial improvement over baseline and the modified baseline procedure (MBP) is only slightly better than baseline. Using this composite outcome index, the level of performance is about the same across all of the aiding configurations in which ΔA or ENR was included.

Table 12 presents summary data on approach and landing outcomes for the alternative go-around advisory concepts. The data in Table 12 indicate that overall performance is somewhat better when the go-around advisories are combined with the GNS or MFD techniques rather than the baseline.

The pattern of within-limit approach and landing outcomes under baseline conditions, or with baseline instrumentation augmented by any of the three go-around advisories, is remarkably consistent. Only 5 of the 24 approaches (21%) were within limits at the Inner Marker and only 6 or 7 were completed with an in-limit touchdown (25%). However, the number of go-arounds was substantially higher than baseline when the advisories were available to the pilot.

When a go-around advisory was paired with either the GNS or MFD technique, the number of within-limit approach outcomes increased to the levels recorded for earlier testing of these techniques. The number of within-limit landings, however, was substantially lower than in the earlier tests and the number of go-arounds increased. Apparently, the emphasis on go-around advisories in this experiment influenced the pilots to execute a missed approach in some instances where the approach might have been successfully completed.

The data obtained in this experiment were also examined to determine the general validity of the go-around advisories in relation to the severity of the shear encounters, the pilot's response to the advisory, and the subsequent approach outcomes. To make this assessment, the performance of the alternative go-around advisory techniques was

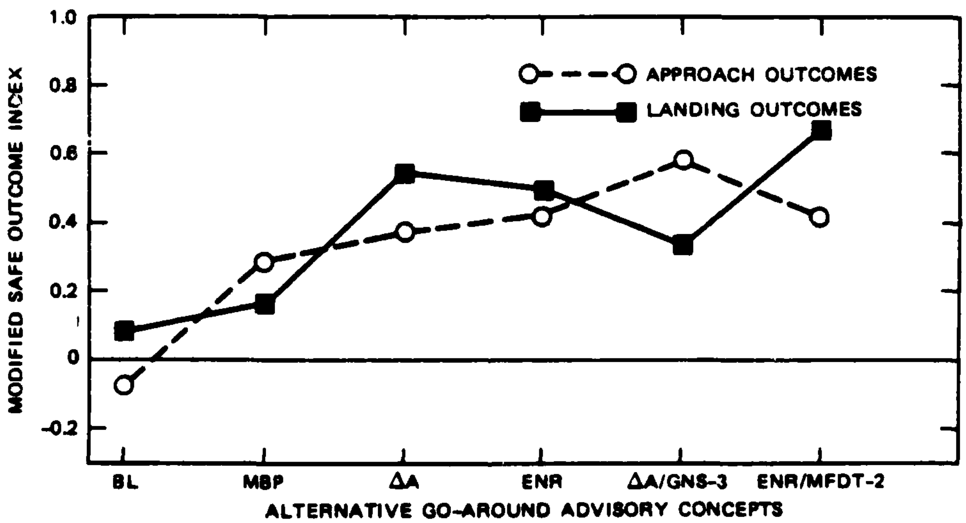


FIGURE 12 PERFORMANCE OF GO-AROUND DECISION AIDS

Table 12

SUMMARY OF APPROACH AND LANDING OUTCOMES
IN THE INITIAL TESTING OF GO-AROUND ADVISORIES

Criterion Measure	Alternative Go-Around Advisory Concept					
	BL	MBP	ΔA	ENR	ΔA/GNS-3	ENR/MFDT-2
1. Number of Within-Limit Approaches (Inner Marker)	5	5	5	5	12	9
2. Number of Within-Limit Landings (Touchdown)	7	4	7	6	9	12
3. Number of Successful Go-Arounds	8	13	14	14	9	9
4. Number of Crashes	2	3	1	1	1	1

classified as either "Correct," "Suspect," or "False," based on the run conditions associated with the occurrence or non-occurrence of an advisory. A count was then made of the number in each category for each of the experimental advisory techniques.

The results of this count are presented in Table 13. In general, advisories were counted as "Correct" when the severity of the shear encounter was severe and the pilot either executed a go-around or ignored the alert and landed out of limits. A "Correct" advisory was also counted when no announcement was made and shear severity was moderate or for either level of shear severity when the pilot managed to keep approach outcomes within limits. Advisories were counted as "Suspect" when they occurred on runs that resulted in within-limit touchdowns or when they occurred on a moderate shear encounter and the pilot executed a go-around that may have been unnecessary. "False" advisories were counted when no advisory was announced and the landing was out of limits, when no advisory was issued on a severe shear encounter and the pilot went around, and when an advisory was issued too late for the pilot to avoid an out-of-limits touchdown or crash.

Table 13

COMPARATIVE PERFORMANCE OF ALTERNATIVE TECHNIQUES FOR PROVIDING GO-AROUND ADVISORIES

Advisory Technique	Number of Advisory Announcements in Each Validity Category[a]		
	Correct	Suspect	False
1. MBP	9	2	7
2. ΔA	11	5	2
3. ENR	12	2	4
4. ΔA/GNS-3	9	6	3
5. ENR/MFDT-2	15	3	0

[a]Based on our analysis of 18 runs for each system. Runs for one pilot are not included because advisory announcements were not recorded.

The data in Table 13 indicate that the best go-around advisory performance was recorded when the energy rate indicator was combined with the MFD technique. "Suspect" or "False" alerts occurred on more than one-third of the runs when the ΔA concept was used, either alone or in combination with the groundspeed technique. The highest "False" alert rate was recorded for the modified baseline procedure (MBP).

Pilot evaluations of the go-around advisory aids were somewhat confounded with their assessments of the GNS-3 and MFD techniques. No clear preferences or endorsements of the ΔA or ENR concepts were expressed, perhaps because of the limited time available to the evaluation pilots to become fully aware of what these new advisories were telling them or to see the devices as believable. The project pilots observing from the right seat felt that the evaluators began to appreciate the utility of the advisories after some experience with them, but were often confused or tended to experiment with them as additional information for control rather than as warning devices. Thus, whenever the ΔA or ENR

indicators moved toward the energy-deficient range, the pilots would add thrust until the indication moved back to the "safe" region. Go-arounds were often delayed until these control actions failed to correct the situation.

The ΔA concept was generally recognized as having more predictive power and might be able to keep the aircraft out of trouble if the advisories were heeded. However, the pilots felt that the ΔA indicator too often indicated a go-around when it did not seem to be appropriate to the situation. The ENR concept seemed to be easier for the pilots to accept, but some felt it would be more useful as the basis for a thrust command than as a go-around advisory.

IV FULL TRIAL

A. Systems Tested

On the basis of initial test results and consultation with the project Technical Monitor at FAA, three aiding concept configurations were selected for a final series of simulation tests. These test exercises were designed to test the various groundspeed, modified flight director, and go-around advisory concepts with a larger group of pilots and to determine the level of operational performance and pilot acceptance that might be expected when these aids were available for coping with the shear encounter. Twenty-six pilots participated in these simulation exercises and included representatives from FAA, airlines, aircraft manufacturers and the Air Force.

The three aiding configurations selected for testing are distinguished by the manner in which groundspeed was displayed, the type of go-around advisory provided, and the availability of the modified flight director and thrust commands. For convenience, the three test configurations will be referred to as:

1. The GNS-3/ENR configuration
2. The GNS-6/ΔA configuration
3. The MFDT-2/ENR configuration

The designators used to identify the major components of each configuration (i.e., GNS-3) are the same as those used in Section III; the reader is referred to the descriptions given in that Section for each component. The designated cockpit displays were the same as those used in initial testing except that the digital readout of computed values of ΔA was not used. Instead, a yellow light was installed on the glare shield, above the airspeed indicator, and was used to indicate the occurrence of a negative ΔA by illuminating and flashing. This light was also used to indicate that computed ENR had exceeded the threshold value for the red zone on the ENR indicator.

The three display arrangements associated with each test condition are shown in Figures 13, 14 and 15. The pilot's basic task was essentially the same using all three configurations, i.e., to fly the approach path by reference to pitch and roll steering commands and to manage airspeed by reference to the Fast/Slow speed command. Inclusion of the ground speed displays and the go-around advisory light in the scan was at the pilot's discretion. Go-around advisories were announced by the First Officer, based on his monitoring of the ENR indicator and advisory light, and pilot response to the advisories was also at his discretion.

B. Evaluation Plan

The effectiveness and acceptance of the aiding configurations just described, relative to a baseline condition defined by conventional DC-10 cockpit instrumentation and approach management technique, has been evaluated in several prior simulation test exercises. The primary concern of the present study was to expose the more promising versions of these aiding concepts to a larger group of pilots and to record their attempts to cope with the low-level shear encounter. For this reason, the tests were not designed to contrast the test concepts with baseline capabilities and emphasis was placed on an individual assessment of the potential benefits of using each of the three selected aids.

Most of the 26 pilots recruited for this stage of testing had no prior experience with the experimental aiding concepts or with the wind shear profiles developed for the tests. All of them were senior pilots with extensive experience in command of large transport aircraft. Average pilot-in-command time was more than 9,000 hours and the average time in the DC-10 was 580 hours. Six of the pilots reported DC-10 time in excess of 1,000 hours and ten were not DC-10 qualified but were high-time pilots in heavy transport aircraft.

It was assumed that the experience of these senior pilots, in attempting to cope with the simulated wind shear encounters on a manually flown ILS approach, would provide a sound basis for estimating the operational potential of the experimental aiding concepts. The primary basis for making these estimates was the data recorded on approach outcomes

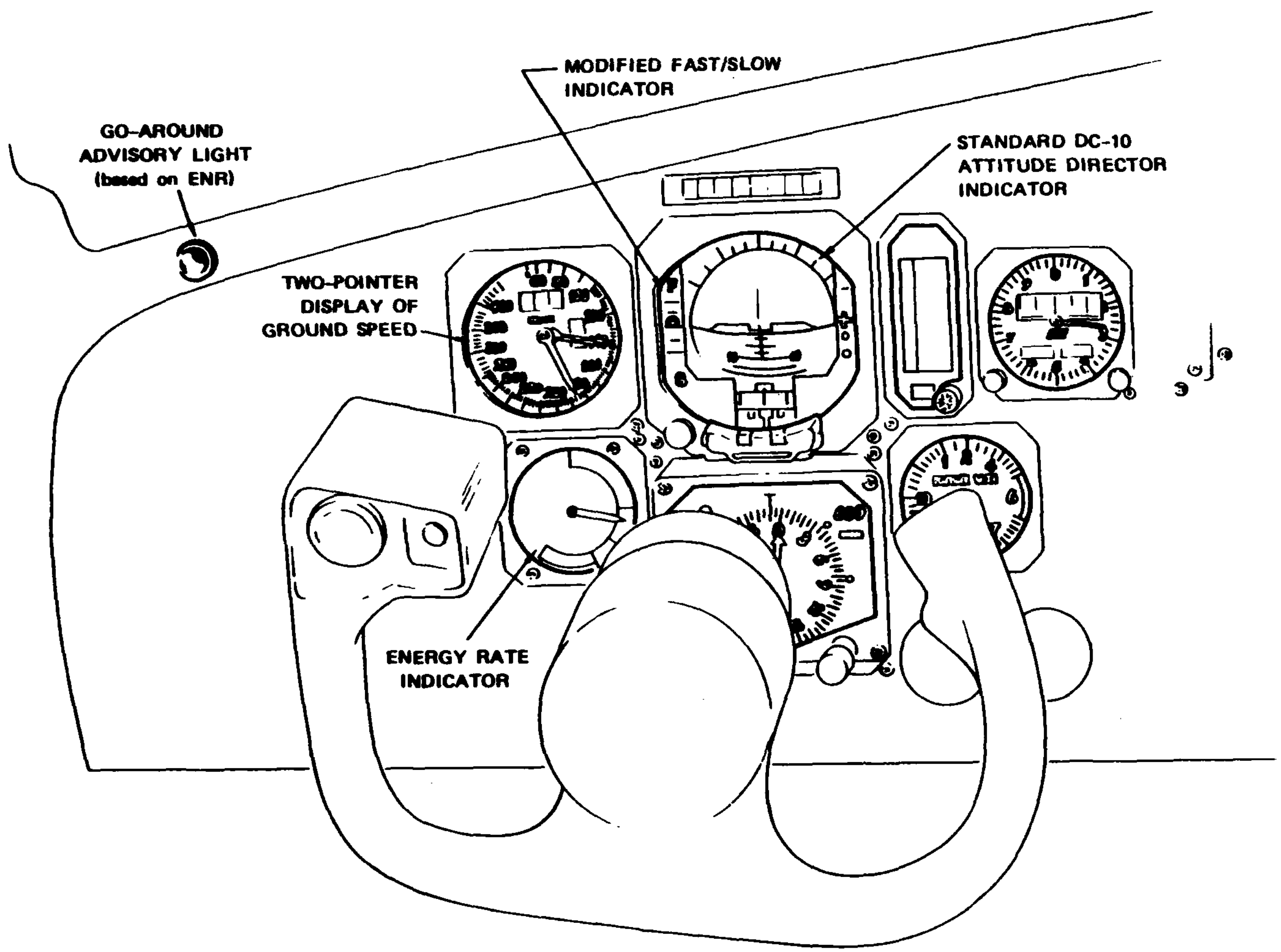


FIGURE 13 SYSTEM GNS-3/ENR

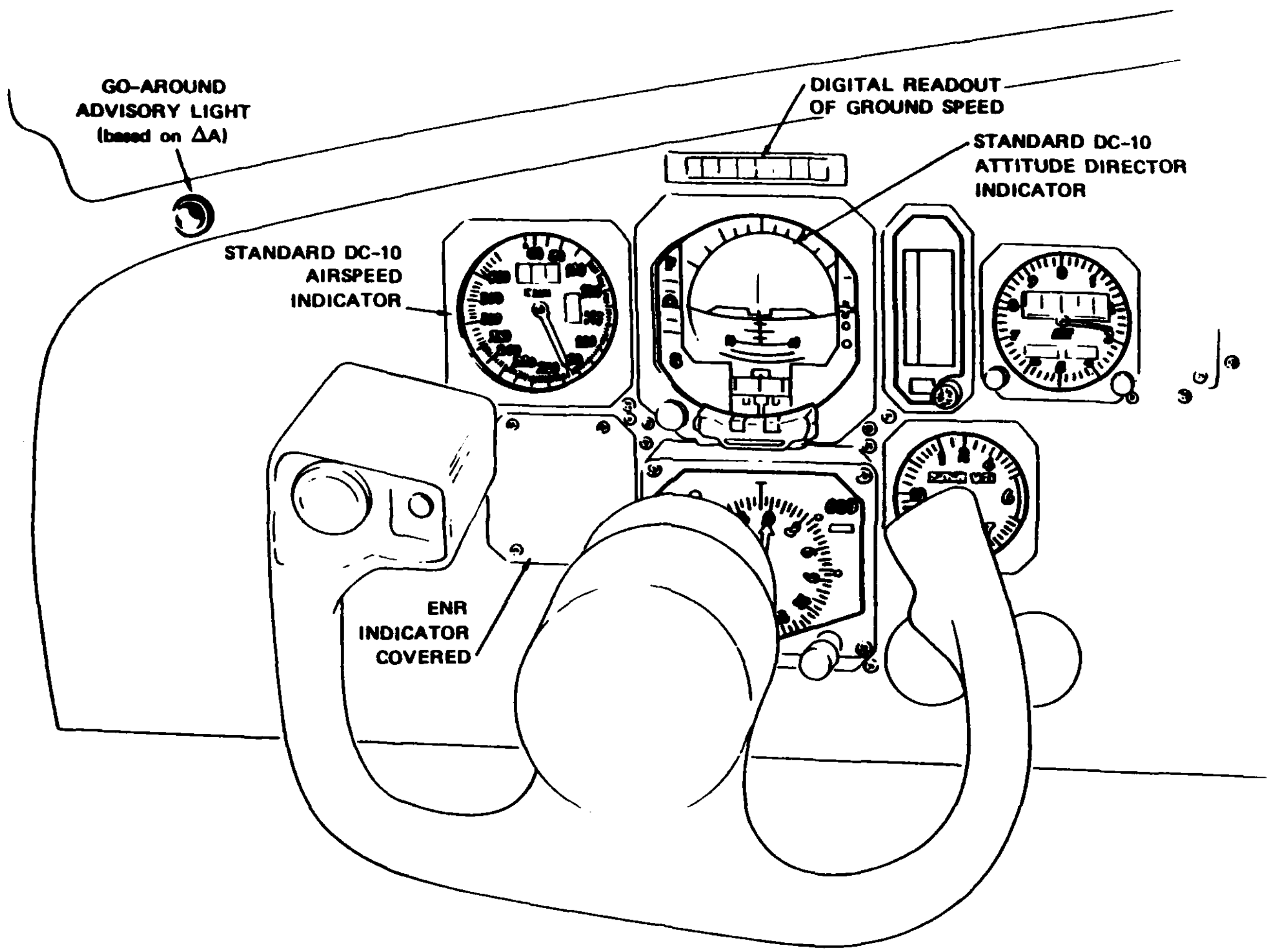


FIGURE 14 SYSTEM GNS-6/ΔA

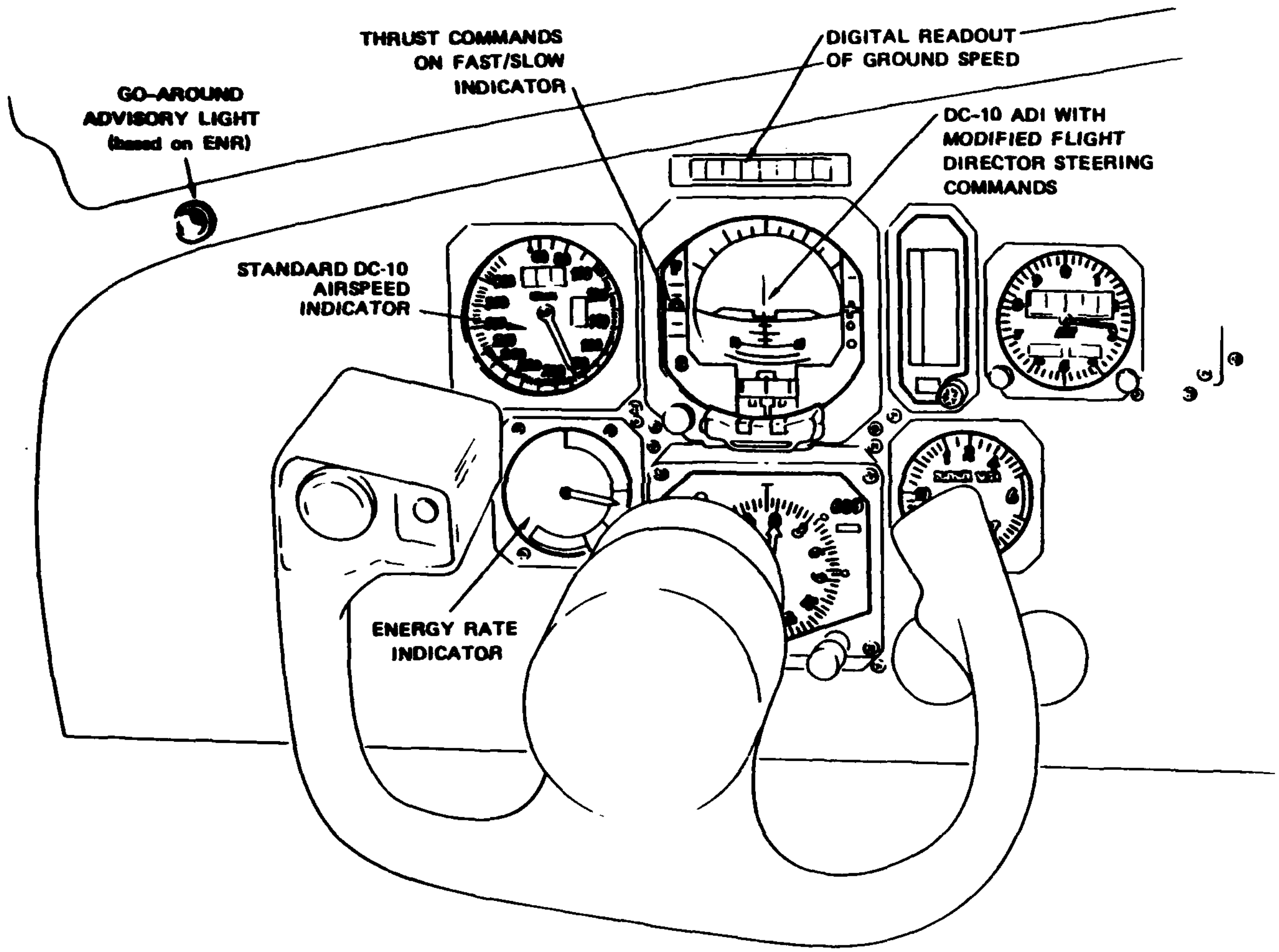


FIGURE 15 SYSTEM MFDT-2/ENR

(i.e., a successful approach terminating with a within-limit landing on the runway, a successfully executed go-around, a touchdown on the runway but exceeding position or velocity limits, or a crash). Objective approach outcome data were supplemented by pilot critiques of the aiding concepts and by their overall assessments of the practicality of the experimental techniques for use in regular airline operations.

The data collection plan adopted for this test exercise is shown in Table 14. Each subject pilot was assigned to fly three sessions in the simulator and was shown a different aiding concept configuration in each session. A single session consisted of 4 training runs on the designated aid followed by 4 data runs and required approximately 40 minutes to complete. Two pilots were scheduled for each day of testing, alternating sessions in the simulator, and the full test schedule for the 26 pilots was completed in 13 days.

Table 14

TEST PLAN FOR FULL-SCALE TESTING OF SELECTED SYSTEMS

Subject Pilot		Test Configuration				
	GNS-3/ENR		GNS-6/ΔA		MFDT-2/ENR	
1	Each pilot flies 4 training runs and 4 data runs using each aid. A different wind shear profile is selected for each run.					
2						
3						
.						
.						
.						
26						
Total Data Runs:	104	+	104	+	104	= 312

As indicated in Table 14, the test plan provided data on a total of 312 runs and allowed estimates of operational performance to be based on 104 runs for each of the aiding configurations tested. Performance against individual wind shear profiles was based on 26 data runs. While contrasts between the alternative aiding configurations was not of prime importance in this study, the test did allow for comparisons of their relative effectiveness. For this purpose, the order of pilot exposure to the alternative aids was counterbalanced to preclude any systematic bias in the data that might be attributed to the carry-over of fatigue, learning or motivation effects from one simulator session to another.

The wind shear profiles selected for both training and data runs are identified in Table 15. The profile designators given in the second column refer the reader to the profile descriptions given in Section II of this report. Notice that the profiles used for training and data runs were not the same. The training profiles were intended to be similar to the data profiles but to enhance realism test data were taken on the pilot's first exposure to a particular shear. For training runs, the shear profiles were always selected in the order shown. The order of exposure to the shears on data runs was scrambled so that pilots would not be able to anticipate the shear condition on their second or third session.

Test procedures and data recording activities were described in Section II. In this test exercise, pilots were briefed to apply their best efforts to complete the approach using the assigned aiding concepts in accordance with the pre-session briefings. The briefings stressed the fact that the decision to continue the approach or go-around was left to the pilot's judgment and that a go-around should be initiated at any time the pilot assessed the flight situation to exceed the limits he would accept for an actual approach. First Officer announcements of go-around advisories and pilot monitoring of the ENR or ΔA indicators were to be treated as advisory information.

C. Approach and Landing Outcomes

As in the Initial Trial, the simulator runs were scored for acceptability in terms of approach outcomes, using the "window" at the Inner

Table 15

WIND SHEAR PROFILES SELECTED FOR

FULL-SCALE TESTING

Wind Profile	Type	Severity
Training Runs:		
1	Boundary Layer	Moderate
6	Thunderstorm	Moderate
8	Thunderstorm	Moderate
9	Thunderstorm	High
Data Runs:		
7	Thunderstorm	Moderate
4	Thunderstorm	High
5	Frontal	Moderate
10	Thunderstorm	High

Marker (100-ft glide slope point) defined by the limits of Table 6, and also in terms of landing outcomes. Because a decision to abort the approach and execute a go-around was the appropriate action on many runs, the most meaningful performance data is that which shows both the go-arounds and the number of acceptable touchdowns. In this Full Trial with the 26 subject pilots we scored a touchdown as "in-limits" if it did not exceed the position, velocity and attitude limits of Table 6, except that instead of the 3000-ft position limit along the runway we used DC-10 stopping limits supplied by Douglas for a 7000-ft runway with normal surface (thrust reverser forces were not used in computing stopping distance). Thus, a landing was scored as acceptable or "in-limits" if it met the Table 6 criteria and also if the combination of touchdown position along the runway, longitudinal touchdown velocity, and longitudinal surface wind indicated that the aircraft would have been able to be braked to a stop without running over the runway end.

The resulting tabulations of landing outcomes for each of the 3 systems tested are shown in the bar charts of Figure 16. For each of the 4 wind profiles of the test runs (training data is not included) the length of a given section of the bar shows the percentage of the runs that fell in the corresponding category: IL for "in-limits," G/A for "successful go-around," etc. The total number of runs in each bar is shown at the top. The runs outside limits are separated according to whether the system's go-around decision aid advised a G/A and was announced by the First Officer, indicated by "A," and whether the simulated aircraft touched down on the runway and would have been able to stop on the runway, indicated by cross-hatching. The most unfortunate category is "G/A attempted, not successful" indicating approaches on which either G/A was advised too late or the pilot failed to respond in time to avoid a bad landing.

As would be expected, the charts show that the high-severity wind shears, profiles 4 (Allegheny at Philadelphia) and 10 (Eastern at JFK Airport), produce a larger number of go-arounds than do the profiles of moderate severity. The combined length of the "IL" and "G/A" categories give the "safe outcome" percentage. These added to the "A" categories show the percentage of runs for which the outcome would have been "safe" if the G/A advisory had been honored; check of the data showed that in every one of the "A" cases the advisory was issued at an altitude high enough for a successful G/A if the pilot responded promptly. In evaluating these results it is important to have a standard of performance to serve as a basis for comparison, particularly since no simulated exercise can be completely realistic even when the experiments have made all reasonable efforts. In an earlier DC-10 wind shear simulation exercise[2] we ran 60 approaches with 16 pilots using baseline approach management (i.e., current conventional instrumentation and flight-director procedures for the DC-10) with wind fields that had no significant wind shear. With the touchdown limits of Table 7 there were 54 acceptable landings, which indicates that a rate of 90 percent "in-limits" landings is the success rate to be expected in a simulation of no-wind-shear current landing operations under comparable visibility conditions. Note that the limits of Table 7 do not include the stopping criterion for a

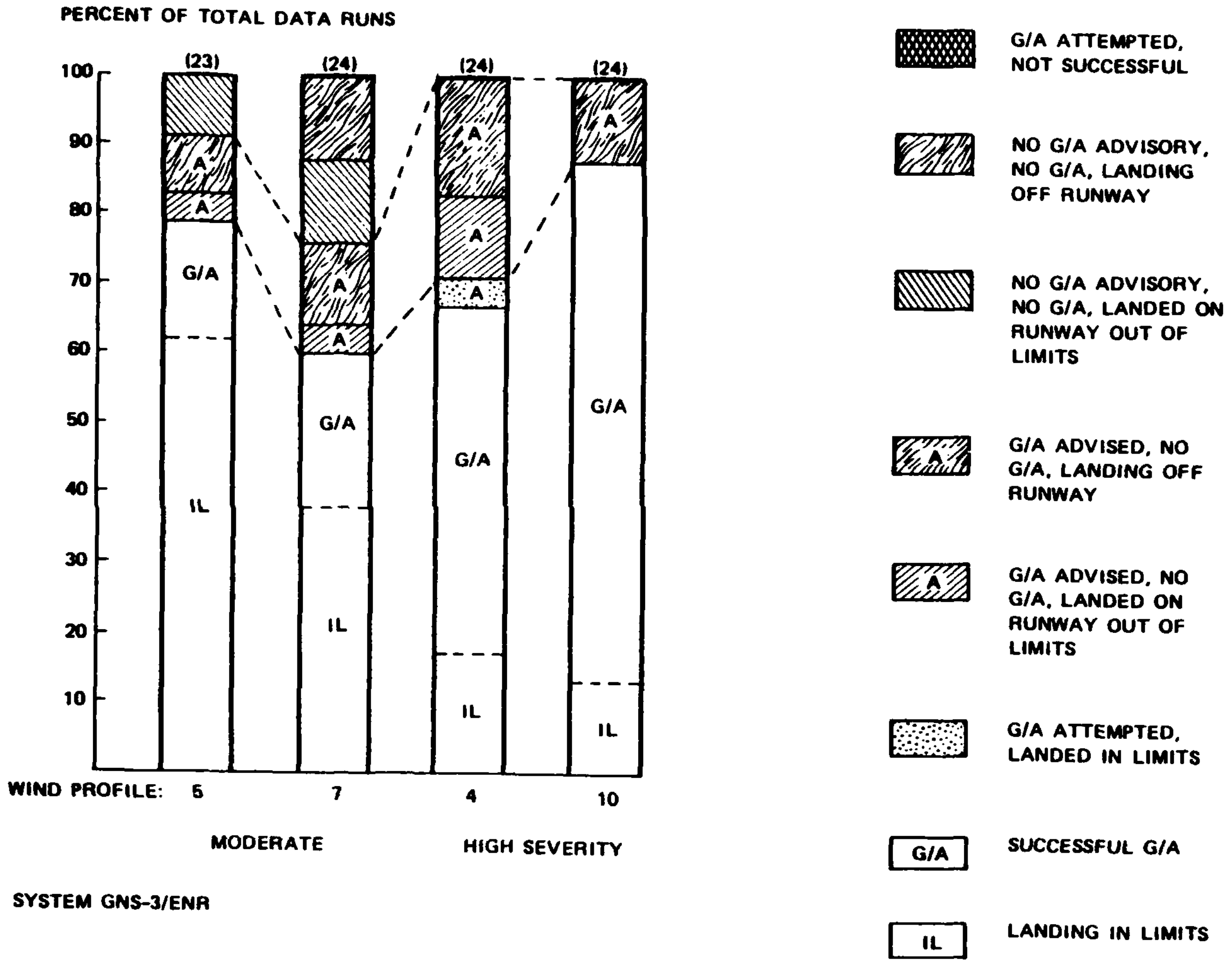


FIGURE 16(a) LANDING OUTCOMES

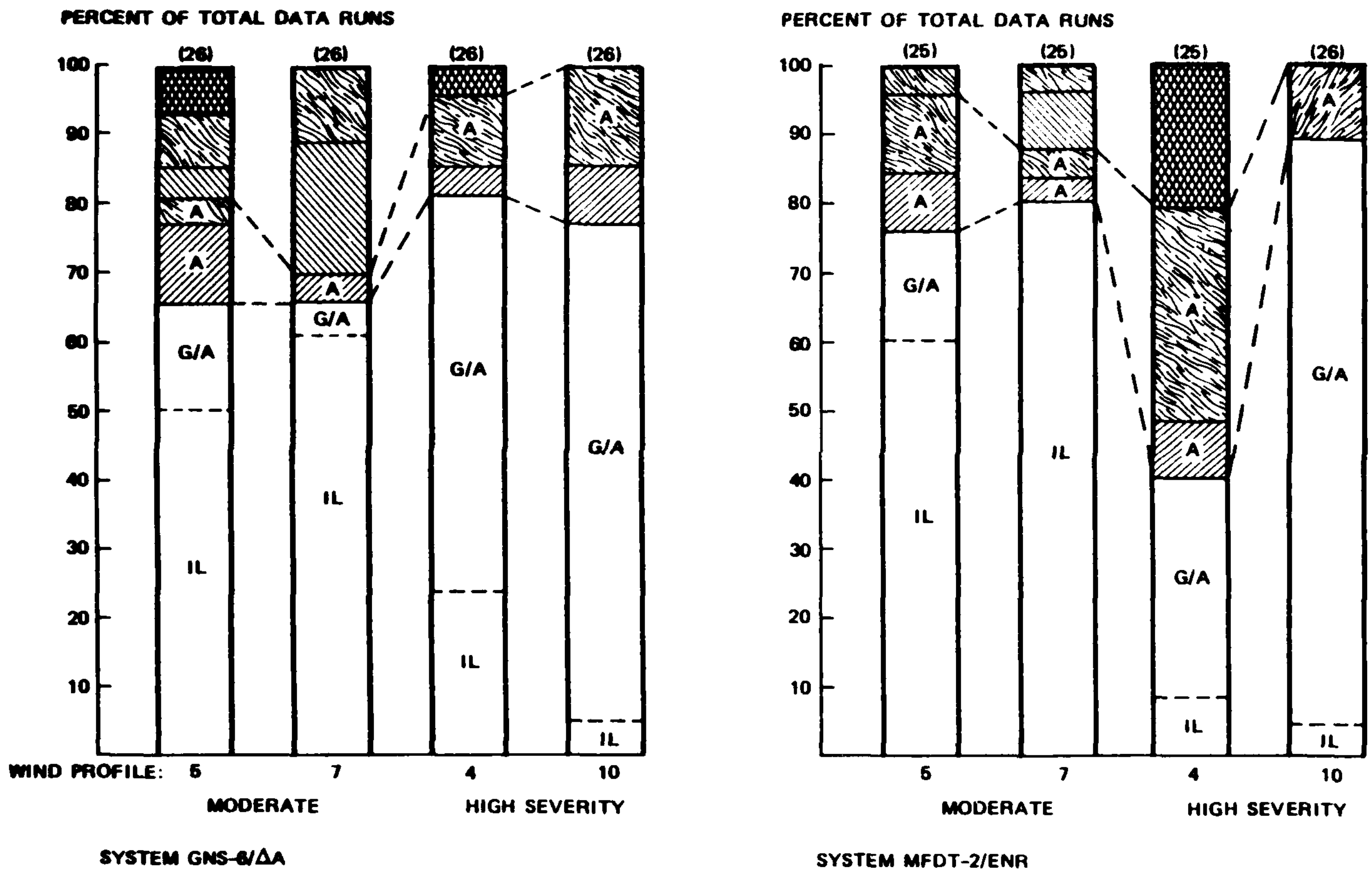


FIGURE 16(b) LANDING OUTCOMES

7000-ft runway and so are not as restrictive as those used here in the Full Trial. The 90-percent standard is probably a little high.

Figure 16 shows that none of the 3 systems tested performed up to the 90-percent standard on all wind profiles. The potential performance--i.e., that we could assume would have been realized if the G/A advisories had been honored--does exceed the 90-percent standard for some of the profiles:

GNS-3/ENR on profiles 5, 4, 10
GNS-6/ΔA on profiles 4 and 10
MFDT-2/ENR on profiles 5 and 10

It is clear that profile 4 (Allegheny at Philadelphia) presented the most difficult problem, particularly for the MFDT-2/ENR system. We do not have a good explanation for the relatively poor performance of this system on this wind field.

Approach outcome data for the three aiding concepts tested are summarized in Table 16. The counts presented in Table 16 are based on the number of data runs (n) indicated in parenthesis at the bottom of each column and thus represent the performance of all 26 subject pilots on the four wind shear profiles. The "Performance Score" is the same as that used in the G/A aid experiment of the Initial Trial.

When the smaller number of data runs on the GNS-3/ENR condition is considered, the approach outcome data shows very little difference in the performance of the three aiding concepts. A contrast with the results of initial testing suggests that the approach outcome data in this Full Trial may represent a somewhat pessimistic projection of the operational performance of the aiding concepts. Most of the subject pilots participated in the full-scale tests (20 of the 26) had no prior experience with the aiding concepts or simulated shear profiles. The better performance of the evaluation pilots in the initial tests may reflect their greater tamiliarity with the aids. A more important performance factor, however, may have been the complexity of the aiding concept configurations tested and the fact that the pilots were exposed to three different configurations in one day of testing.

Table 16

SUMMARY DATA ON APPROACH AND LANDING OUTCOMES FOR THE FULL-SCALE TESTING OF SELECTED AIDS

	Aiding Concept		
Criterion Measure	GNS-3/ENR	GNS-6/ΔA	MFDT-2/ENR
1. Number of Within-Limit Approaches (Inner Marker)	41	40	45
2. Number of Within-Limit Landings (Touchdown)	31	36	38
3. Number of Successful Go-Arounds	39	39	34
4. Number of Crashes	7	8	18
5. Performance Score	38%	39%	39%

The pattern of approach and landing outcomes using each aiding concept is illustrated in Figures 17 through 22. Flight path offsets at the Inner Marker are plotted in the first three figures, using numerals to locate the position of the aircraft relative to the glide slope and localizer. The numerals identify the wind shear profiles selected on each run and the dotted box defines the limits adopted for assessing approach outcomes. Touchdown positions are plotted in Figures 20 through 22, using a similar coding scheme and with the positions along the runway represented on the x-axis.

These graphic representations of approach and landing outcomes show less dispersion in lateral offsets at both the Inner Marker and touchdown when the MFD technique is used. However, this technique also produced a comparatively greater number of vertical offsets below the lower limit and more short landings, especially on wind profile #4. Otherwise, the pattern of outcomes for the three aiding configurations is quite similar, with a somewhat tighter pattern of within-limits outcomes indicated for the GNS-3/ENR configuration.

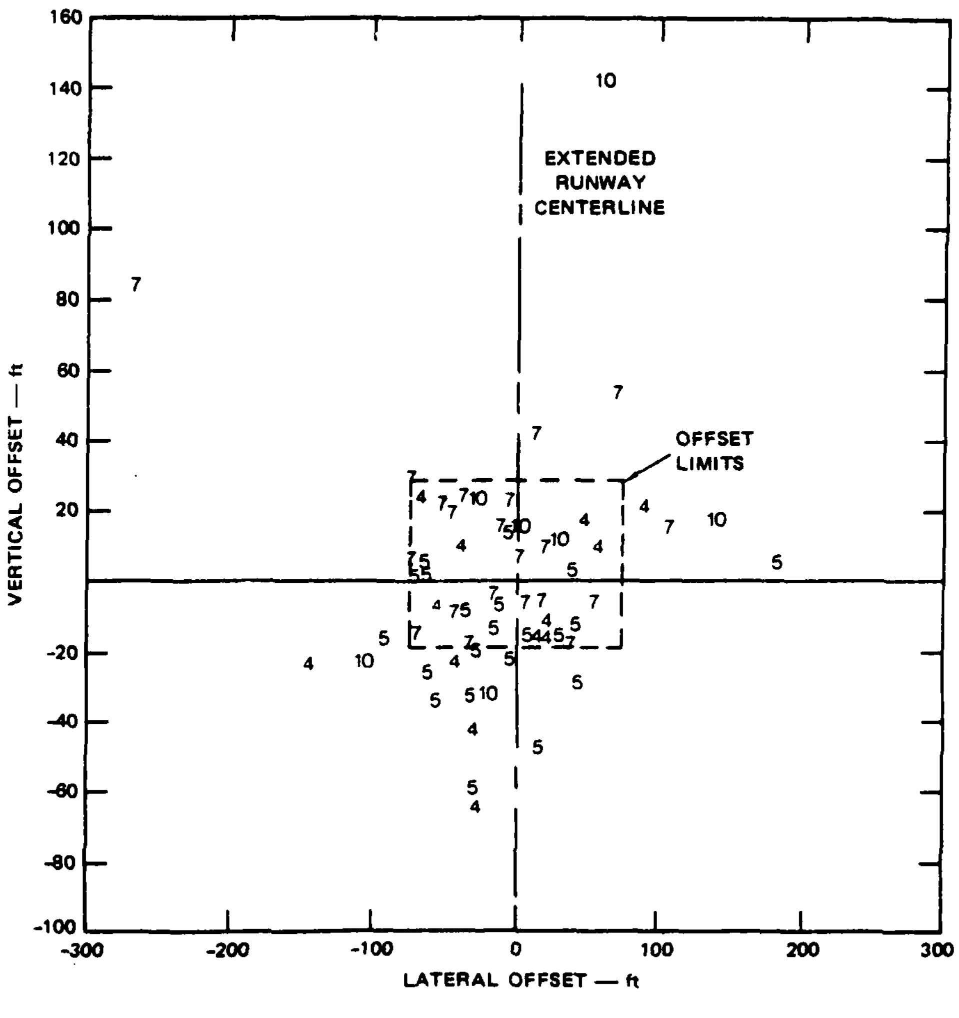


FIGURE 17 POSITION DISPERSIONS AT INNER MARKER WITH GNS-3/ENR

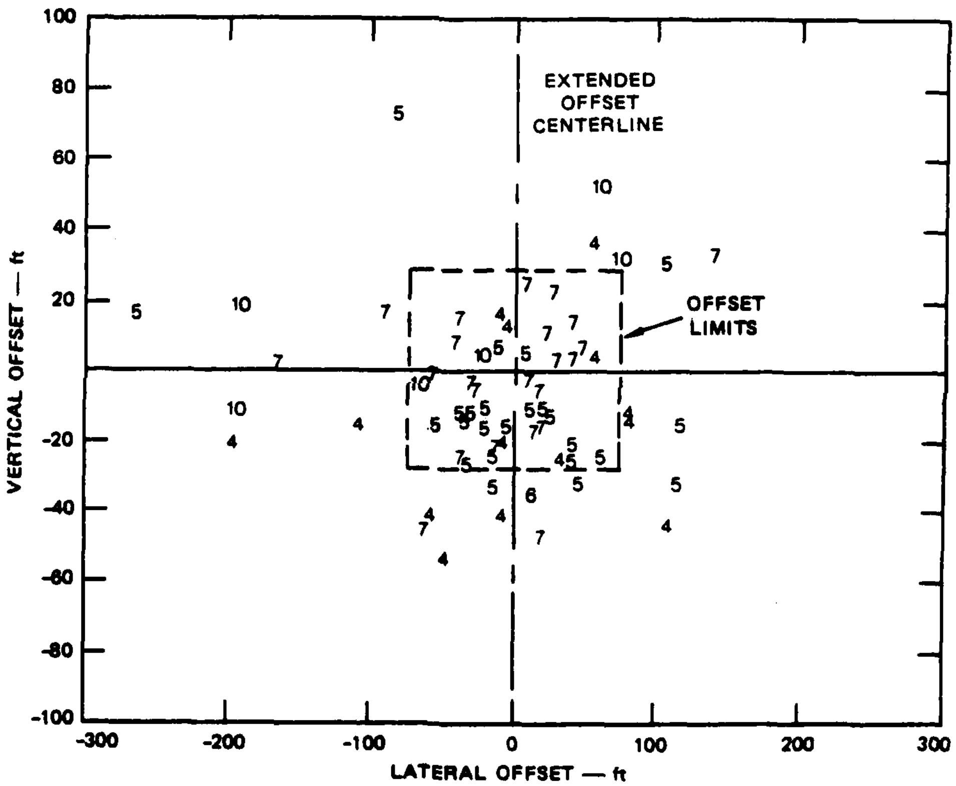


FIGURE 18 POSITION DISPERSIONS AT INNER MARKER WITH GNS-6/ΔA

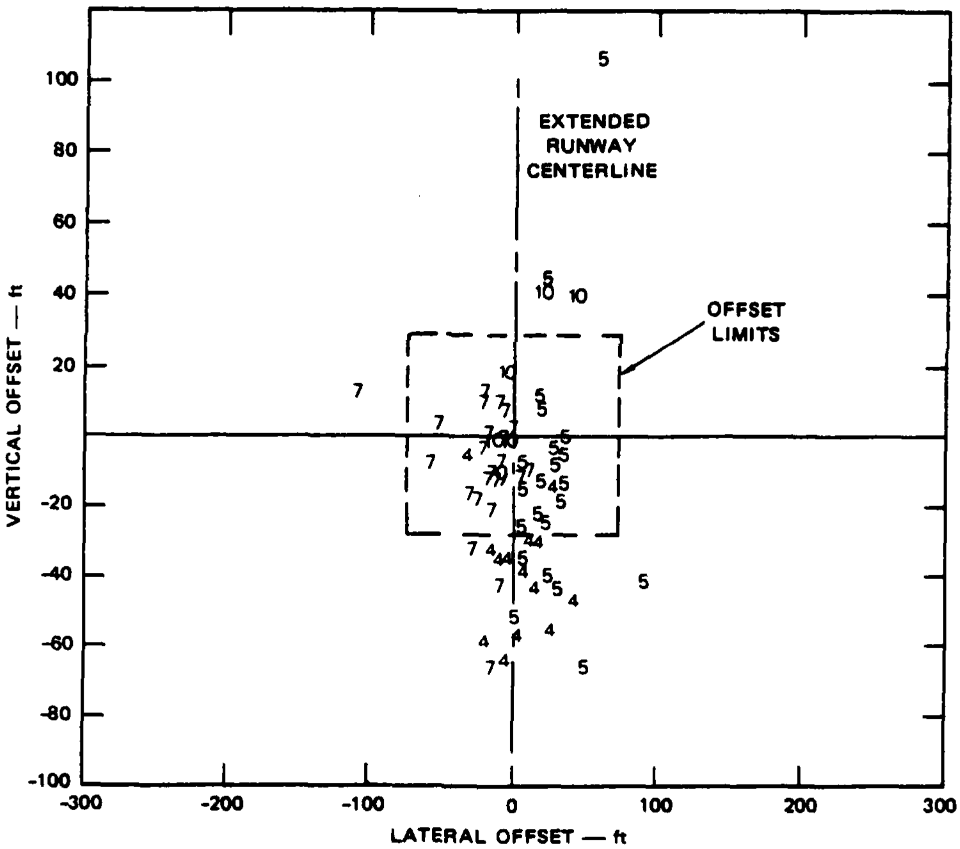


FIGURE 19 POSITION DISPERSIONS AT INNER MARKER WITH MFDT-2/ENR

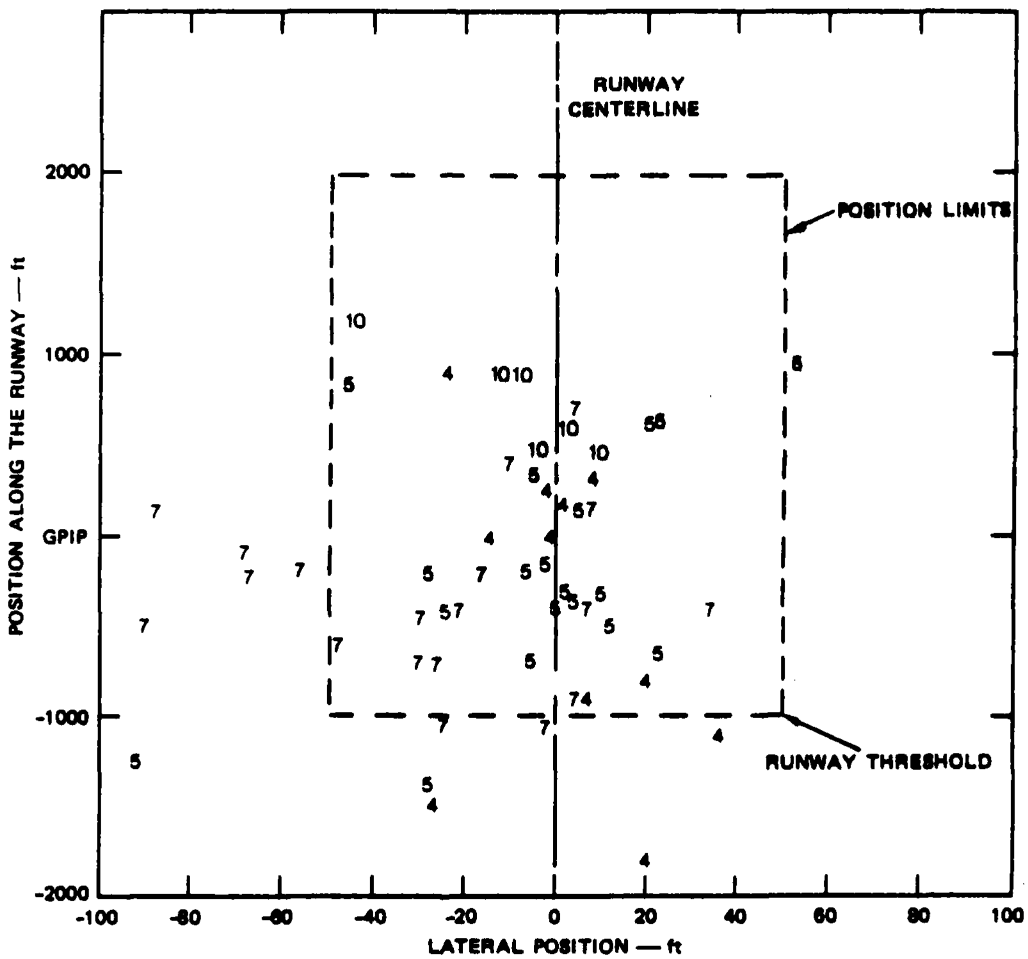


FIGURE 20 POSITION DISPERSIONS AT TOUCHDOWN WITH GNS-3/ENR

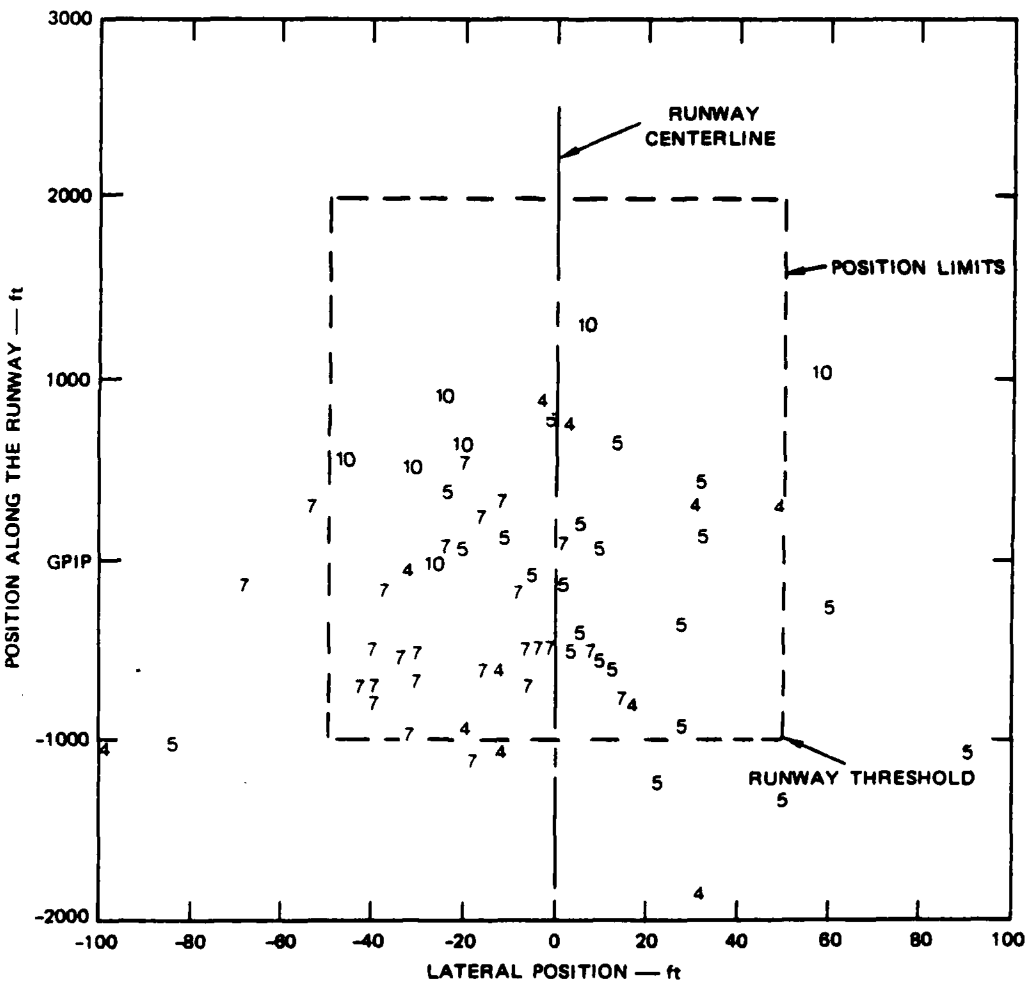


FIGURE 21 POSITION DISPERSIONS AT TOUCHDOWN WITH GNS-6/ΔA

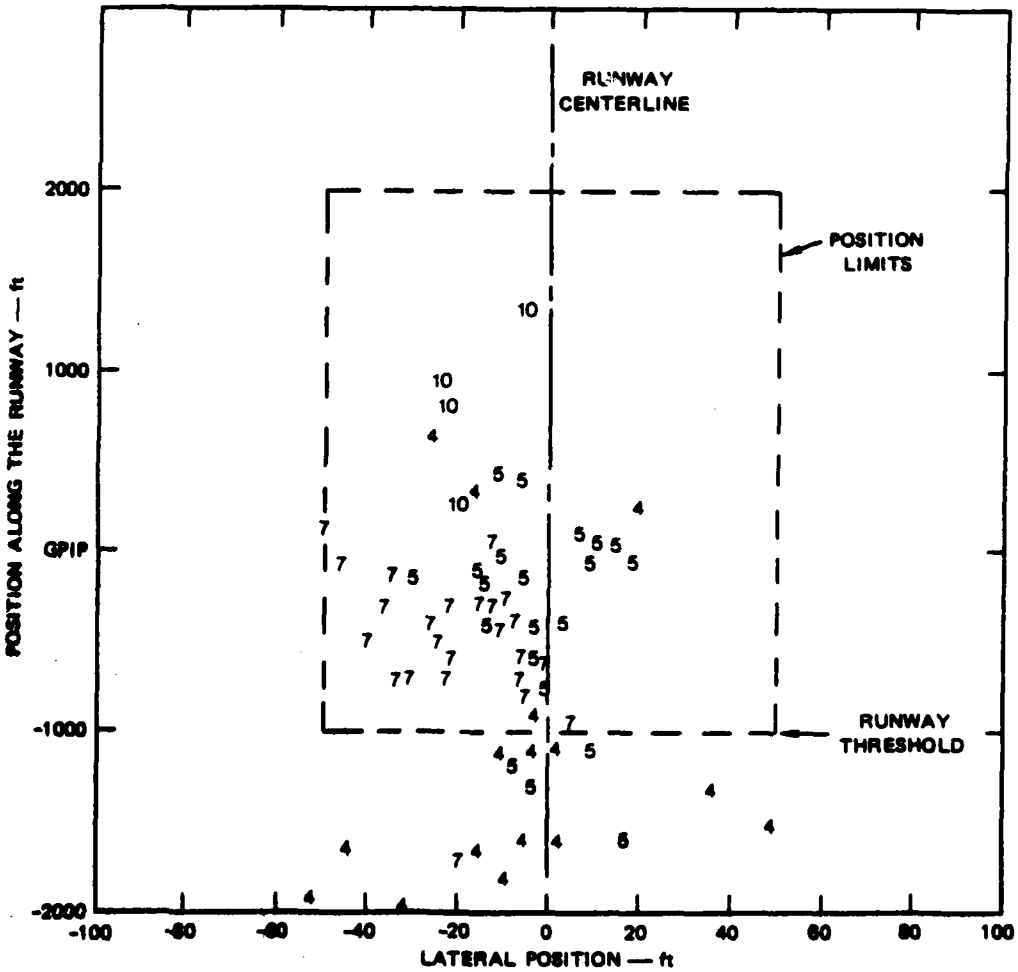


FIGURE 22 POSITION DISPERSIONS AT TOUCHDOWN WITH MFDT-2/ENR

The data in Figure 16 indicate that the aiding concepts may be more effective for the severe shear conditions. As expected, a larger proportion of within-limit approaches were recorded for the moderate shears. However, more go-arounds were executed on the severe shears, particularly on profile #10, and there were fewer out-of-limit outcomes on runs with no go-around advisory given to the pilot. The bar diagrams also show the differences in the performance of the aiding concepts on each of the test shear profiles.

The validity of the go-around advisory announcements was assessed using the same advisory classification scheme as that described for the initial testing. Table 17 presents the counts of advisory announcements for each validity category for each combination of aiding concept and wind shear severity level. The "Correct Advisory Index" at the bottom of the Table shows a clear trend toward more effective advisory announcements for the severe shear profiles. The performance of the MFDT-2/ENR configuration on the severe shears confirms the initial test results showing that the best advisories were given when the energy rate indicator was paired with the MFD technique. However, note that the highest "False" alert rate was recorded when this aiding configuration was used on the moderate shears.

In general, the data on approach and landing outcomes demonstrate that the aiding configurations tested do provide the pilot with useful information for detecting and avoiding severe wind shear encounters. However, the number of "False" and "Suspect" go-around advisories is unacceptably high and indicates the need for further development of the ENR and ΔA techniques and/or the way they are used by the pilot.

1. Airspeed Management and Flight Path Control

Airspeed management and flight path control are the two basic components of approach management and the various elements of the aiding configurations tested were expected to support and enhance pilot performance of these tasks. The results presented in this section provide an indication of how well the pilot was able to perform the tasks when each of the aiding concepts were used.

Table 17

VALIDITY OF GO-AROUND ADVISORY ANNOUNCEMENTS
FOR EACH AIDING CONCEPT BY LEVEL OF SHEAR SEVERITY

(Cell Entries are the Number of Advisory Announcements in each Validity Category)

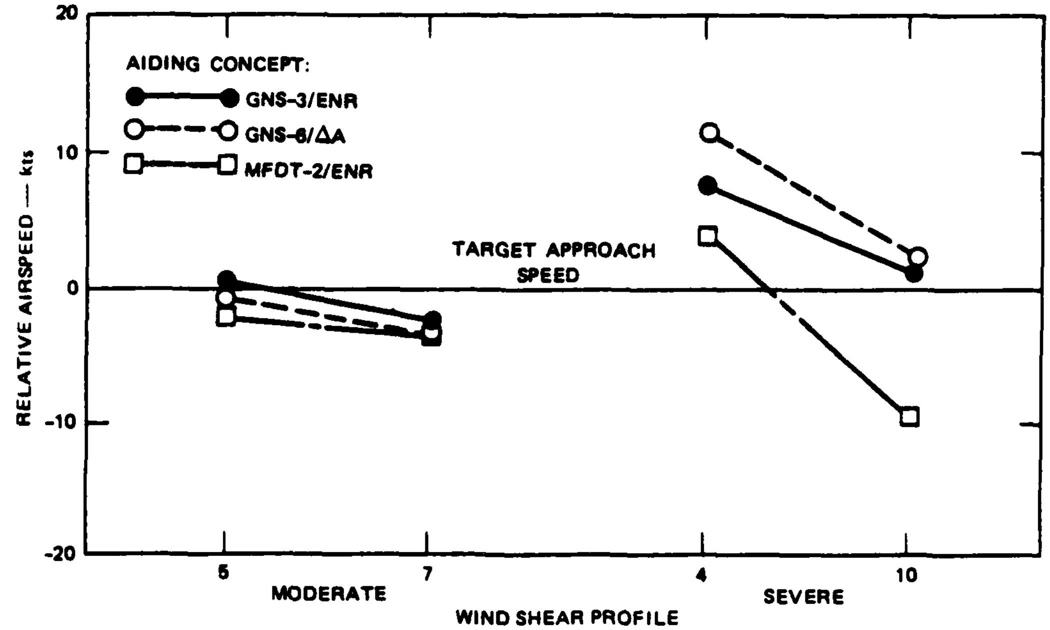
Validity Category	GNS-3/ENR Mod.	GNS-3/ENR Severe	GNS-6/ΔA Mod.	GNS-6/ΔA Severe	MFDT-2/ENR Mod.	MFDT-2/ENR Severe
Correct	29	35	33	40	30	47
Suspect	11	6	15	4	7	1
False	7	7	4	8	13	3
Total data runs:	47	48	52	52	50	51
Correct Advisory Index[2]:	61%	73%	63%	77%	60%	92%

(Column heading: Aiding Concept and Shear Severity)

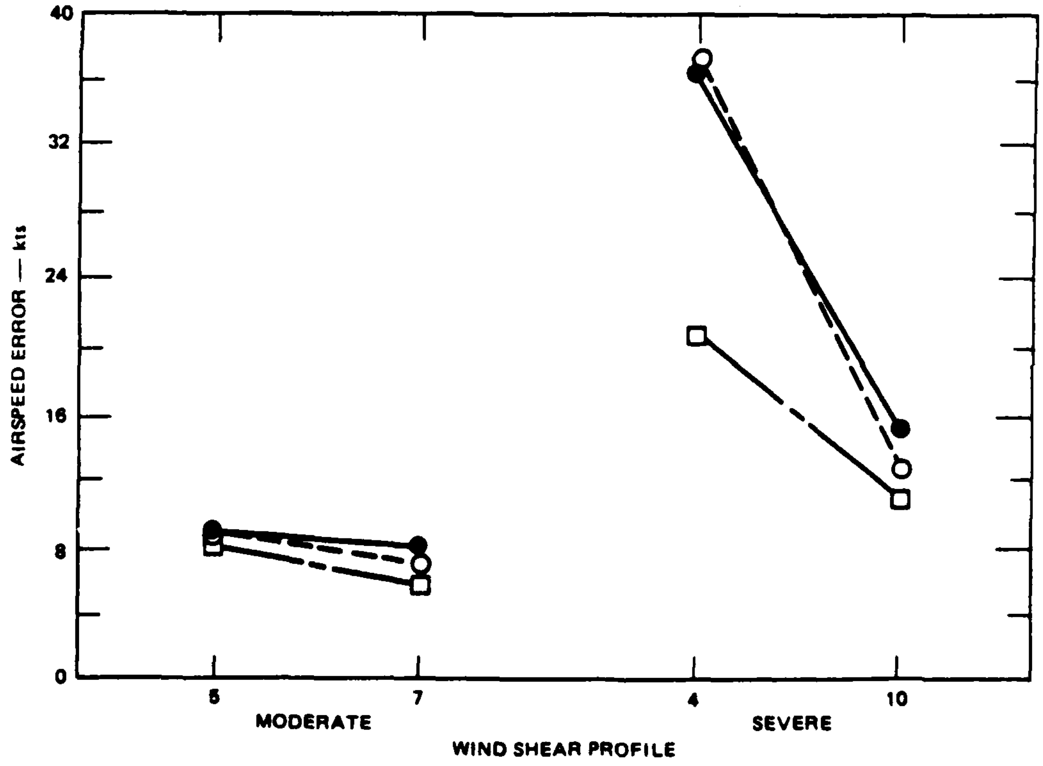
[2]Ratio of number correct to total data runs, expressed as a percentage.

a. Airspeed Management

Display support for airspeed management was provided by the modified Fast/Slow speed command in all three aiding configurations. The computational algorithms for deriving the speed commands were designed to prevent any substantial drop in indicated airspeed during the shear encounters by calling for an airspeed pad based on the minimum pre-planned groundspeed technique (see description in Section III for details). The data plot in Figure 23a shows that all three aiding configurations were effective in this regard. The maximum drop in airspeed below the pilot-selected target approach speed (V_{REF} + conventional additives based on surface wind reports) was less than 5 knots for all three aids on the moderate shears. On the severe shears, airspeed was maintained at or above target approach speeds except for the 10-knot drop recorded when the MFDT-2/ENR technique was used on profile #10.



(a) MAXIMUM DROP IN AIRSPEED OVER THE 500-TO-100-ft APPROACH SEGMENT, AVERAGED ACROSS PILOTS



(b) RMS AIRSPEED ERROR OVER THE 500-TO-100-ft APPROACH SEGMENT, AVERAGED ACROSS PILOTS

FIGURE 23 AIRSPEED MANAGEMENT DURING THE LOW-LEVEL SHEAR ENCOUNTERS USING EACH AID

The data plot in Figure 23b shows the impact of carrying the airspeed pad on conventional airspeed management. Mean displacements (rms) from target approach speed (airspeed error) over the 500 to 100-foot approach segment, where most of the shear activity occurred, are plotted for each wind shear profile. Since airspeed drop was less than 10 knots over this approach segment, as shown in Figure 23a, the rms airspeed errors shown generally represent the magnitude of the airspeed required to fly the minimum pre-planned groundspeed technique. The data indicate that this pad was substantial on the severe shears but generally less than 10 knots on the moderate shear encounters.

The effectiveness of the aiding techniques in actually maintaining groundspeed at or above the pre-selected minimum (target groundspeed) is shown in Figure 24. The data show that pilots were generally able to keep the drop in groundspeed to less than 10 knots for both moderate and severe shears using the modified Fast/Slow speed command associated with GNS-3 and GNS-6. When the thrust command developed for the MFDT-2 technique was used, groundspeed drop averaged more than 20 knots. This difference was expected and is due to differences in the computational algorithm for the MFD thrust command (see Figure 10, in Section III). In the thrust command algorithm, the gains applied for groundspeed management were set at half the value of the gains applied for maintaining target airspeeds and groundspeed was thereby allowed to drop below its reference value to a greater degree than in the modified speed command.

Figure 25 shows the effects of carrying the excess approach speeds on landing performance. The plot at the top of this figure shows average touchdown positions along the runway and indicates a general tendency for the aircraft to touchdown in the first 1000 feet of the runway, i.e., short of the glide path intercept point (GPIP). With no excess speed in this approach, nominal touchdown positions would be expected to be about 500 to 600 feet beyond the GPIP. The touchdown positions recorded on wind profile #10 were about 200 feet beyond this nominal touchdown zone. Note that when the MFD technique was used on wind profile #4, average touchdown positions were very short--right at the runway thres-

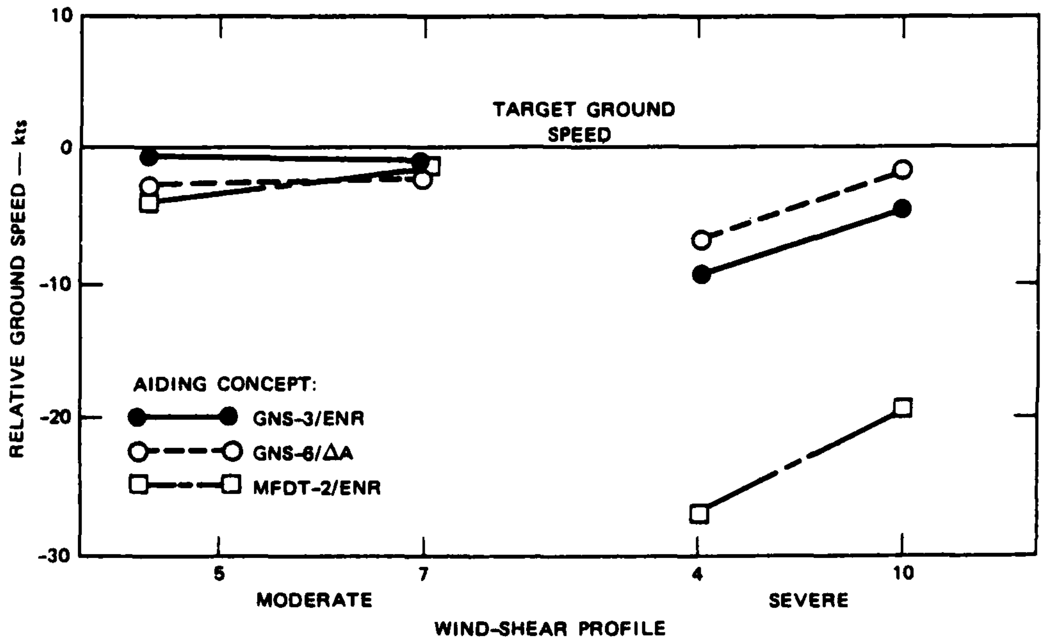
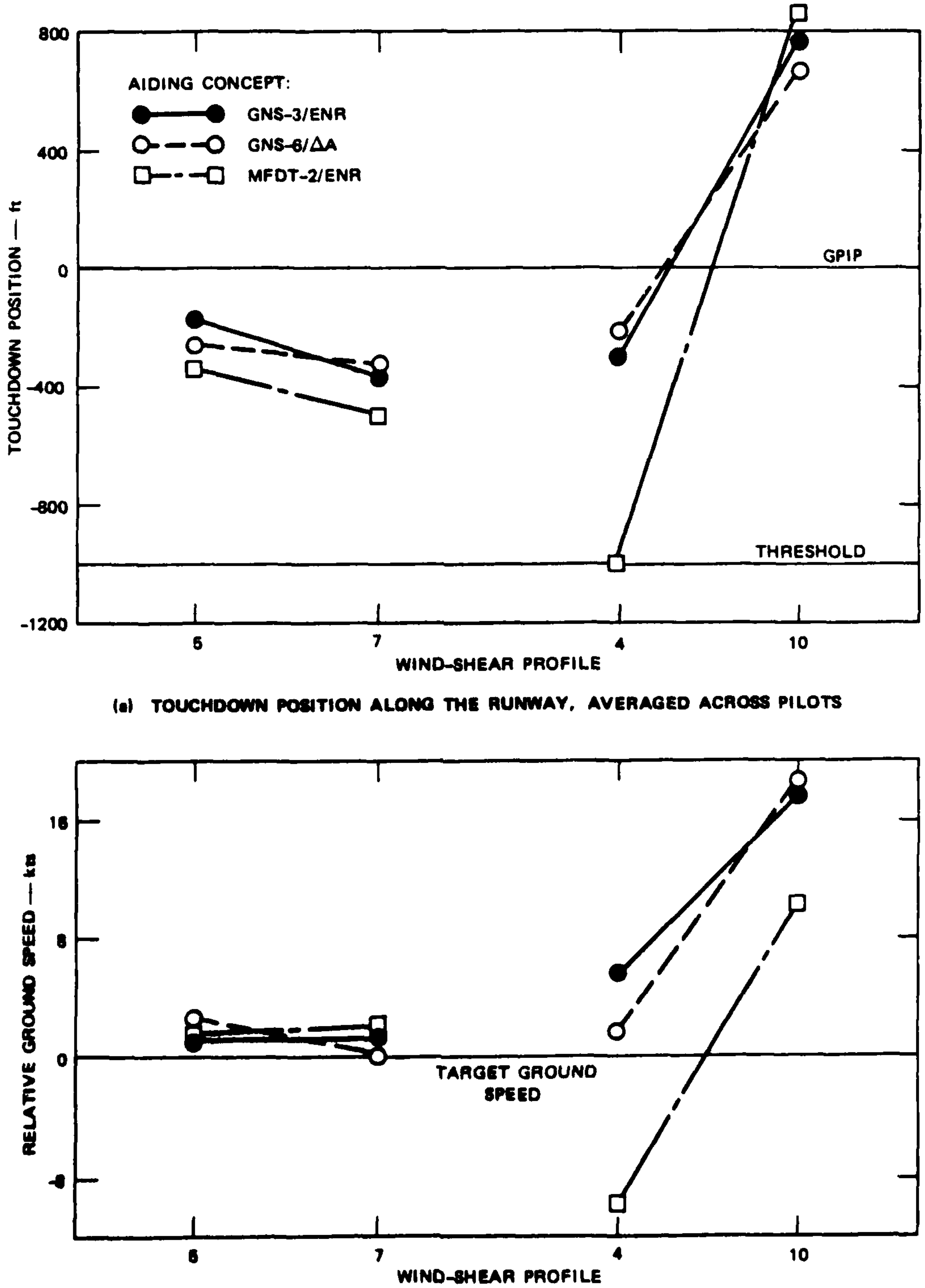


FIGURE 24 MAXIMUM DROP IN GROUNDSPEED OVER THE 500 TO 100-FT APPROACH SEGMENT (averaged across pilots)



(a) TOUCHDOWN POSITION ALONG THE RUNWAY, AVERAGED ACROSS PILOTS

(b) MEAN DEVIATION FROM SELECTED TOUCHDOWN SPEED, ACROSS PILOTS

FIGURE 26 EFFECTS OF AIRSPEED MANAGEMENT TECHNIQUES ON TOUCHDOWN POSITION AND GROUNDSPEED

hold. Figure 23b shows that the average airspeed pad on this profile was more than 20 knots and it is clear that excess approach speed on this type of shear encounter does not lead to long touchdowns.

Another concern relating to carrying excess airspeed on the approach is that touchdown speeds might be higher than normal and lead to stopping problems and/or excessive stress on braking systems and tires. The plot in Figure 25b shows the average groundspeeds at touchdown relative to the desired (target) groundspeed for reported surface wind conditions. Touchdown speeds were not excessive for three of the wind profiles, including profile #4 on which the highest airspeed pads were recorded (see Figure 23b). However, average speeds as high as 18 knots above the target speed were recorded on wind profile #10 and, on a short runway at the corresponding touchdown positions shown in Figure 25a, this level of excess speed could lead to serious stopping problems.

b. <u>Flight Path Control</u>

Display support for this task component was provided by the standard DC-10 flight director, when the GNS-3 and GNS-6 aids were used, and by the modified flight director steering commands when the MFDT-2 techniques was used. Summary data on the accuracy of glide slope and localizer tracking with these techniques are presented in Figures 26 and 27 for each wind profile. Data points in these plots are rms deviations from the glide slope (vertical offset) and localizer (lateral offset) over the 500 to 100-foot approach segment that have been averaged over the 26 pilots.

The accuracy of glide slope tracking was somewhat better using the MFD, except for the cross-over shown on profile #10 for the GNS-6/ΔA concept. However, except for the obvious superiority of the MFD recorded on profile #4, the differences between the two flight directors for glide slope tracking was not substantial in this experiment. A marked improvement in the accuracy of localizer tracking was recorded for the MFD on all four wind profiles, as shown in Figure 27.

The data plots in Figure 28 provide an indication of how closely the subject pilots were able to follow the pitch and roll steer-

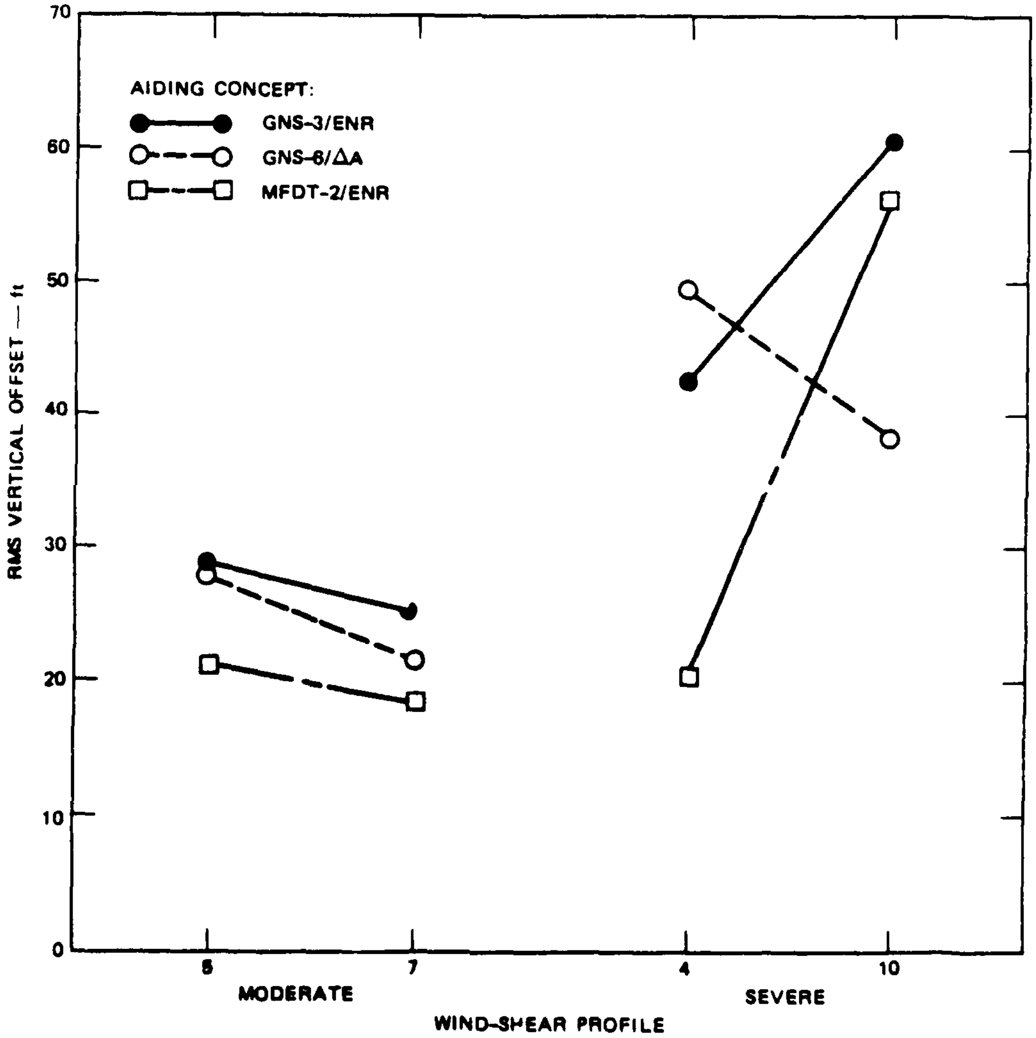


FIGURE 26 GLIDE SLOPE TRACKING ACCURACY DURING LOW LEVEL SHEAR ENCOUNTERS

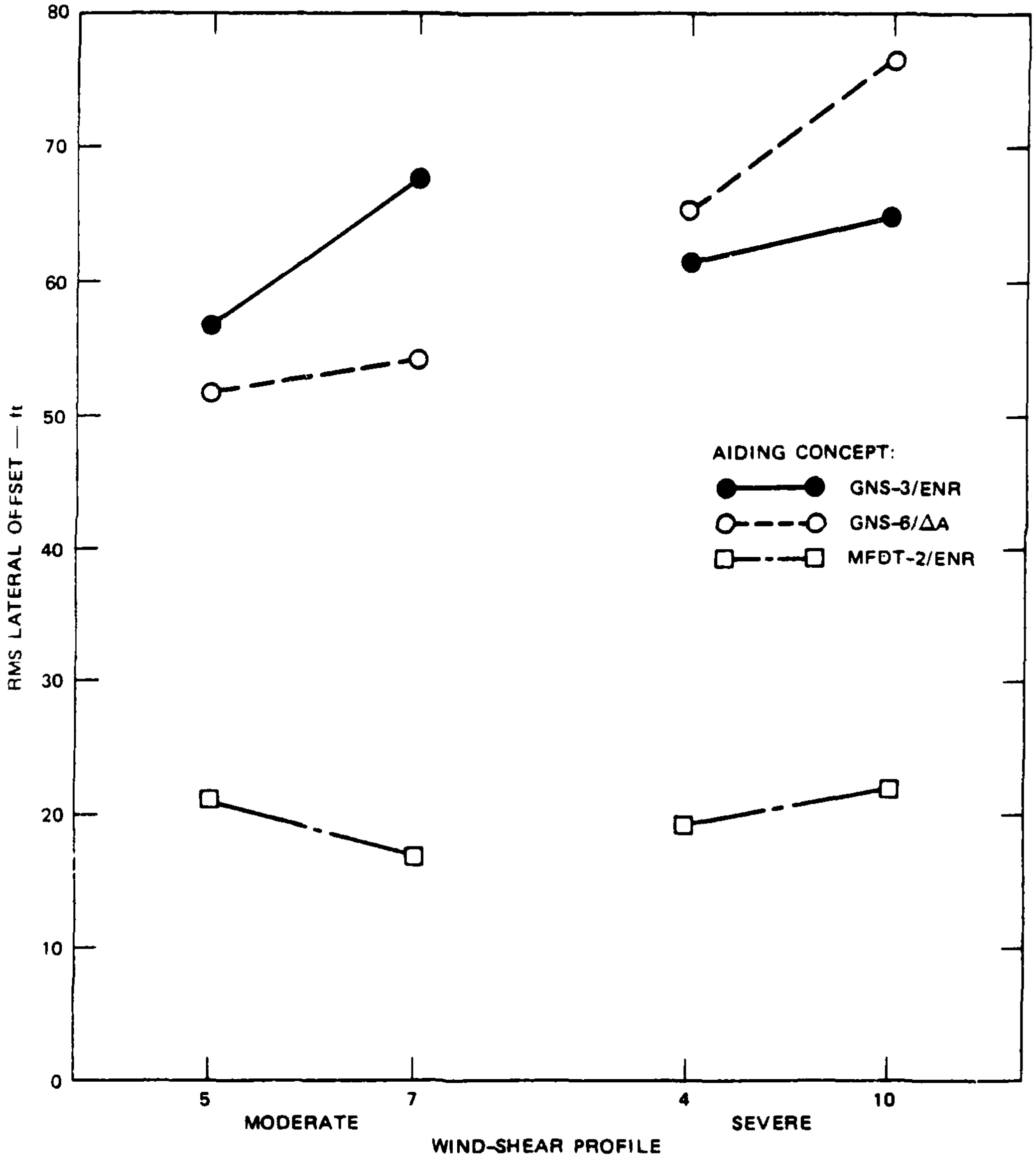
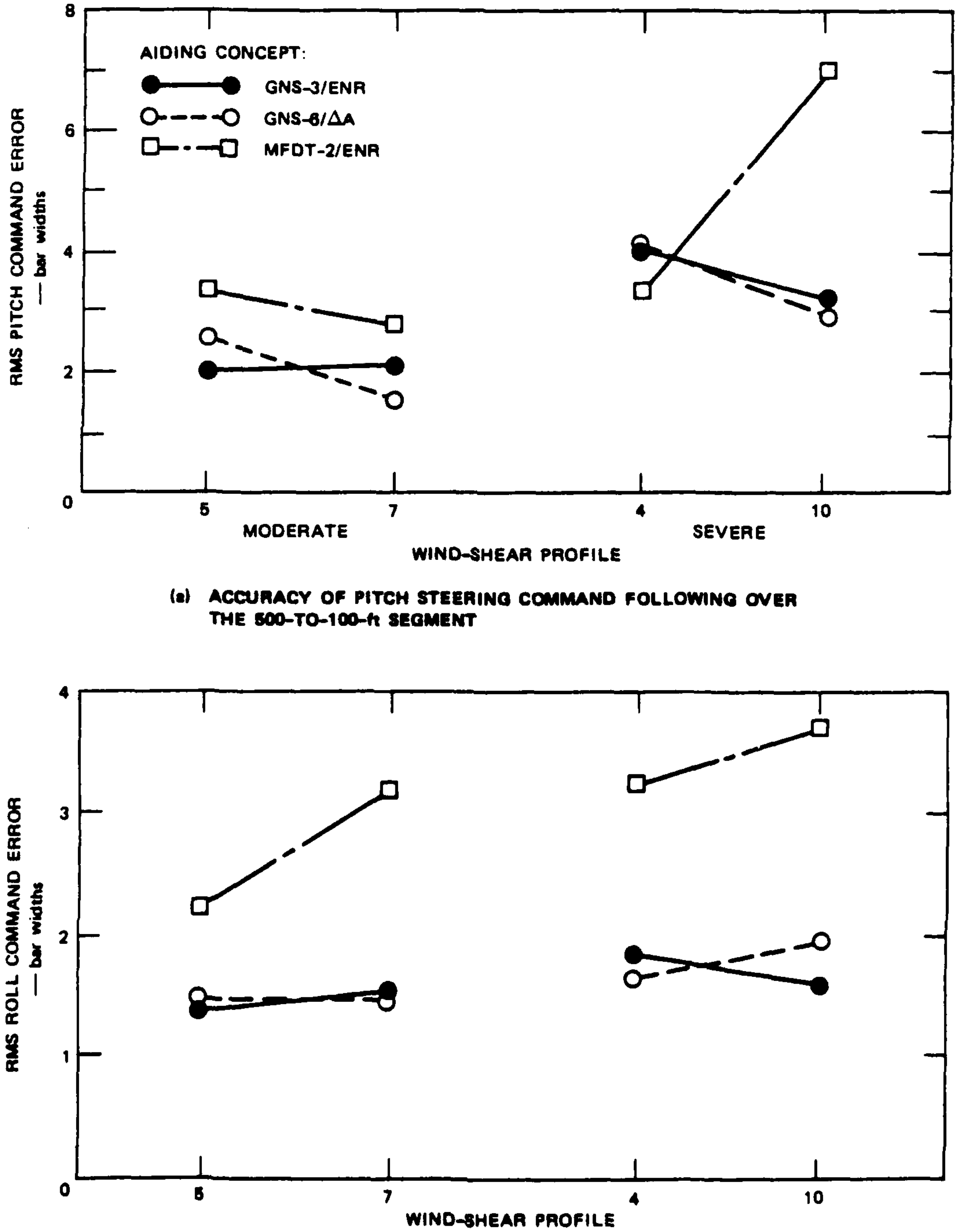


FIGURE 27 LOCALIZER TRACKING ACCURACY DURING LOW LEVEL SHEAR ENCOUNTERS



(a) ACCURACY OF PITCH STEERING COMMAND FOLLOWING OVER THE 500-TO-100-ft SEGMENT

(b) ACCURACY OF ROLL STEERING COMMAND FOLLOWING OVER THE 500-TO-100-ft SEGMENT

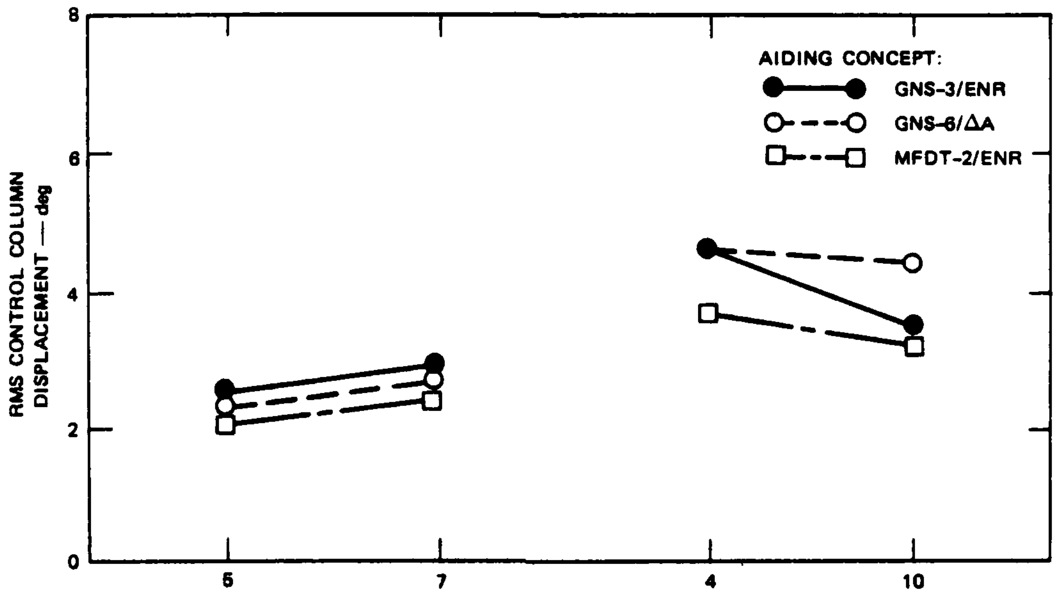
FIGURE 28 ACCURACY OF FLIGHT DIRECTOR COMMAND FOLLOWING DURING LOW LEVEL SHEAR ENCOUNTERS

ing commands using the conventional and modified flight directors. The more abrupt and more active changes in steering commands represented on the MFD were apparently more difficult for the pilots to follow closely, as indicated by the consistently higher command bar displacements for all shear profiles. The comparatively poor following of pitch steering commands on profile #10 may account for the poor glide slope tracking shown in Figure 26. More accurate localizer tracking was obtained with the MFD in spite of the poor roll steering command following shown in Figure 28b.

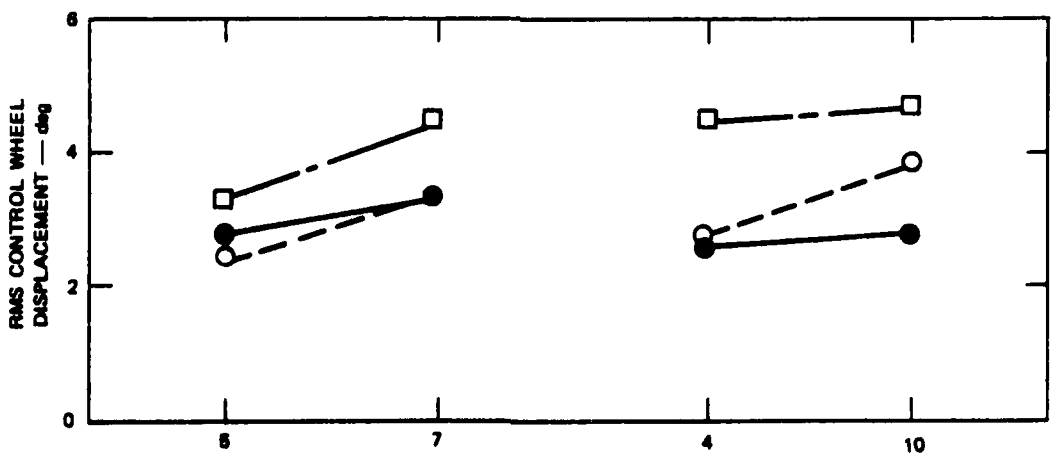
2. Pilot Workload and Acceptance

In the debriefing sessions following each set of data runs in the simulator, pilots were asked to consider how hard they worked using the aiding concepts they had just been exposed to and to rate the workload relative to that required for a conventional ILS approach. A five-point rating scale was used for this assessment and the number of pilot ratings at each level on this scale is given in Table 18 for each aiding concept. It was somewhat surprising to note that most of the pilots rated the aiding concepts as "Somewhat Easier" and some rated them "Much Easier" than conventional approach management technique. Perhaps the pilots were indicating that it would be harder to cope with the wind shear encounters without having the aids available and were not addressing the issue of having more things to do. In any event, there is little indication that pilots would feel that the experimental techniques would involve an increase in pilot workload.

A more objective indication of pilot workload on the flight control task was obtained using a measure of control activity. Figure 29 presents the average magnitude of control column (pitch axis activity) and control wheel (roll axis activity) displacements over the 500 to 100-foot approach segment. No appreciable differences in control activity were recorded for the alternative aiding concepts, though a slightly higher level of roll axis activity is indicated for the MFD on the severe conditions. These data also support the contention that the use of the experimental aids, in this case the MFD, would not involve an increase in workload.



(a) MEAN CONTROL COLUMN DISPLACEMENTS OVER THE *500-TO-100-ft* APPROACH SEGMENT, AVERAGED ACROSS PILOTS



(b) MEAN CONTROL WHEEL DISPLACEMENTS OVER THE 500-TO-100-ft APPROACH SEGMENT, ACROSS PILOTS

FIGURE 29 CONTROL ACTIVITY DURING LOW LEVEL SHEAR ENCOUNTERS

Table 18

PILOT WORKLOAD RATINGS

Workload Rating*	GNS-3/ENR	GNS-6/ΔA	MFDT-2/ENR
	Aiding Concept		
1. Much Easier	7	7	11
2. Somewhat Easier	13	17	10
3. About the Same	1	2	2
4. Somewhat Harder	3	0	2
5. Much Harder	0	0	1
Σ:	24	26	26
$\bar{X}$:	2.00	1.81	1.92

*Relative to the workload for conventional approach management

Pilot acceptance ratings for the aiding concepts tested are given in Table 19. On the basis of their experience with each aiding concept, pilots were asked to indicate, on a five-point rating scale, the level of confidence they would have in their ability to cope with actual wind shear encounters like they were exposed to in the simulator. The ratings given indicate that pilot acceptance of the techniques for actual flight operations would be positive, but no substantial difference in their acceptance across aiding concepts is apparent.

In their last debriefing session, the subject pilots were asked to rank order the three aiding configurations to indicate the one they would most like to have available for actual shear encounters. The MFDT-2/ENR was the first choide of 14 of the 26 pilots and the remaining pilots were about evenly divided in their preferences for the GNS-3/ENR and GNS-6/ΔA concepts. Further elaboration on pilot acceptance of the aids for routine operational use is provided in the following discussion of pilot comments.

Table 19

PILOT ACCEPTANCE RATINGS

Acceptance Rating	Aiding Concept GNS-3/ENR	GNS-6/ A	MFDT-2/ENR
5. Highly Confident	6	5	6
4. Confident	9	10	12
3. Somewhat Confident	8	11	6
2. Uncertain	0	0	1
1. Not at all Confident	1	0	1
Σ:	24	26	26
$\bar{X}$:	3.79	3.77	3.81

3. Pilot Critique of the Aiding Concepts

Subject pilot comments relating to the effectiveness and operational utility of the aiding concepts are summarized in this section. This discussion is based on both the debriefing interviews and on the observations of project pilots who were in the simulator with the subject pilots on all training and data runs. The pilots seemed to prefer to treat the various components of the aiding concepts separately, rather than as integrated aiding configurations such as the GNS-3/ENR modified fast-slow command/energy rate combination. For consistency, then, these components will also be treated separately in this discussion.

a. The Two-Pointer Display of Groundspeed

Most of the subject pilots like the idea of having groundspeed displayed on the airspeed indicator using a second pointer, as they did in earlier tests of this display concept. Some of them reported difficulties in confusing the two needles in their initial experience with the concept but felt that this would not be a problem as they became more familiar with the display. The pilots who liked this display said that its most useful feature was the close association with airspeed informa-

tion and the direct indication this provided for assessing winds on the approach and anticipating the potential shear.

b. The Digital Readout of Groundspeed

Eleven of the 26 pilots liked the digital readout better than the two-pointer display, perhaps because it was simple and did not get them involved in interpreting groundspeed/airspeed relationships. The location of the readout above the ADI was highly acceptable and easy to include in the pilot's scan. The project pilots observed that little use was made of either groundspeed display during the approach, due to the demands of the flight director and because the airspeed management task could be accomplished by satisfying the Fast/Slow command. The potential difficulties in using the digital readout for maintaining a pre-planned minimum groundspeed during the approach were thereby avoided.

The project pilots also noted that the principal use of the groundspeed information occurred at the start of the approach. It was used with airspeed to estimate the headwind-tailwind component at altitude and then compared with the surface wind report to assess the potential shear condition. For this purpose, the digital readout was as acceptable as the two-pointer display.

c. Modified Fast/Slow Indicator

Subject pilots were nearly unanimous in their acceptance of this technique for airspeed management. Having the speed command available for keeping both airspeed and groundspeed above minimums, without having to include either the airspeed indicator or the digital readout in their scan, was considered essential by most pilots. The use of this indicator was judged to be very effective in maintaining both speed minimums and the pilots, generally, did not think it necessary to cross-check the airspeed/groundspeed indicators to interpret or verify the command information. The expanded scaling on this indicator (± 20 knots full scale) was either preferred over the conventional ± 10 knot scaling or not considered objectionable by the pilots.

d. Modified Flight Director

The MFD was preferred over the standard flight director by more than two-thirds of the pilots and most of the pilots felt that they could do a better job of flight path tracking using the MFD. The main objections to the MFD, as in earlier testing of this concept, were that ". . .it would give the passenger a very rough ride" and that it was ". . .just a bit too quick," especially in the roll axis. Some of the pilots felt that the gains should be reduced to some value between those used for the standard steering commands and those driving the MFD. Two pilots, both FAA engineering test pilots, felt that the MFD could not be certified as it is presently mechanized and they expressed strong doubts about line pilot acceptance of the highly demanding command following task.

The project pilots observed that when pilots did not follow the commands closely and got behind, the steering bar excursions were indeed too abrupt and extensive. However, in some instances, pilots tracked the pitch commands very closely and found them to be more manageable. In this experiment, the sensitivity in the roll axis seemed to be greater than in earlier testing and nearly all of the pilots found this feature to be unacceptable.

Both project pilots felt that the modified steering commands were a definite help in negotiating the shear encounters and that the subject pilot performance using the MFD was better than on the standard director. They observed that the standard pitch steering commands seemed heavily damped, with altitude changes up to 5 degrees producing little or no change in the command. While these commands were comparatively easy to follow, glide slope tracking was characterized by large, long term oscillations about the glide path with consequent pitch instability and large power changes required for speed management. The MFD, if closely followed, was quick enough to avoid these large excursions from the glide slope and resulted in better pitch stability and more precise tracking.

e. <u>The Energy Rate Indicator</u>

Fourteen of the 26 subject pilots preferred this indicator over the Acceleration Margin (ΔA) light for the go-around advisory and the ΔA indicator was the first choice for 6 of them (the other 6 wouldn't choose one over the other or felt that they were both unacceptable). The most common reason given for preferring the ENR display was that this instrument provided trend information by showing needle movement from the green zone toward the alert (yellow) and hazard (red) zones of the indicator (see description in Section III). A display of this kind could have been provided for ΔA, but in this experiment the only display was a flashing light to indicate that ΔA had reached a critical value.

The ENR indicator was observed to be highly sensitive to thrust changes and in most instances, pointer movements toward the hazard zone could be rapidly checked or reversed simply by increasing thrust. However, when conditions were really bad (i.e., high sink rate, airspeed drop), additional thrust would not bring the pointer back toward the green zone and a hazardous situation was clearly indicated. By this time, the situation was also clear from other instruments and the ENR did not add any new information.

The sensitivity of the ENR indicator to thrust changes also produced numerous nuisance or false indications in the red zone and pilots understandably tended to ignore this warning feature. As in the initial tests, the tendency was to use it as a reminder that some sort of energy deficiency was occurring and to cross-check other instruments to determine the necessary control action. The availability of the warning after these control actions were ineffective was characterized by one of the observer pilots as ". . .like being told you'd just stepped off a cliff, and were being advised to jump back."

f. <u>The Acceleration Margin Indicator</u>

This technique was generally accepted as providing a more reliable basis for the go-around advisory and pilots reported that the flashing light was an effective way to get their attention. Both project pilots observed that there were substantially fewer false or nui-

sance alarms given by the ΔA light, as compared with the ENR indicator, and that after some experience with this device, most of the pilots could appreciate the predictive character of the ΔA alert. The most objectionable feature of this technique was the lack of trend information, i.e., an indication that ΔA was moving forward the critical value of insufficient thrust capability.

One of the project pilots commented that by the time the ΔA light illuminated, a go-around attempt was often unsuccessful because acceleration capability at that time was only sufficient for maintaining level flight with the aircraft still in the landing configuration. He observed that reducing drag by going to the go-around flap setting did help, but there appeared to be large increases in induced drag when the go-around was initiated at lower than normal approach speed and speeds often dropped quickly to the stick shaker region.

g. General Comments

Subject pilot acceptance of the DC-10 simulation and the representation of wind shear conditions was highly positive, as it was in earlier studies using the Douglas facility. No sessions were missed due to simulator down-time and pilot comments on the fidelity of the simulation, especially the cab motion and the turbulence effects, were quite favorable. Project pilots observed that the approach sequence may have been initiated too close in (runs were started at a glide slope height of 1500 feet) and that initial conditions were not always accurately reflected on the instruments before the run was started (i.e., groundspeed below selected reference, wind component not accurately reflected on the two-pointer airspeed and vertical speed indicators).

The major difficulty with the test design was that the aiding configurations were probably too complex for the subject pilots to fully assimilate and use correctly in the time available to each pilot in the simulator. The three configurations consisted of two types of groundspeed display, two forms of flight director steering commands, two different fast-slow commands, and two different techniques for providing go-around advisories. In many instances, the subjects were

saturated by the second or third session and it is unlikely that the technical and operational features of the aiding concepts were fully appreciated. Performance data therefore reflects the fact that pilots were still somewhere on the low end of the learning curve and it is likely that there was some confounding of the results for various components of a particular aiding feature or use concept was difficult to distinguish or assess.

4. Takeoff Outcomes

Takeoff sequences were flown against four versions of a thunderstorm wind profile and one milder frontal shear condition. The five wind profiles selected for the examination of takeoff performance are identified in Appendix A as profiles 11 through 15. The four thunderstorm profiles are characterized by a substantial headwind shearout. On three of the four wind profiles, the headwind shearout occurs in combination with downdrafts in excess of 10 knots. The frontal shear represents a milder loss in the headwind component and is accompanied by a downdraft of less than 5 knots.

Pilots were briefed to execute a normal, full-thrust takeoff and reference speeds were based on the simulated takeoff gross weight of 407,000 lbs. Takeoff runs were included in the scheduled simulator sessions on a time-available basis and data were obtained on 8 of the 26 subject pilots. Only minor variations in aircraft response to the shear conditions were observed across pilots.

Typical aircraft responses to the shear encounters on takeoff and climbout are shown in the strip chart recordings reproduced in Figures 30a through 30e. A plot of the longitudinal, lateral and vertical wind components actually encountered by the aircraft is provided on channels 4, 5 and 6. The top three plots provide a corresponding time history of altitude above ground level (AGL), vertical speed, and indicated airspeed.

These plots show that the encounter with all four versions of the thunderstorm shear are extremely hazardous. Crashes were recorded

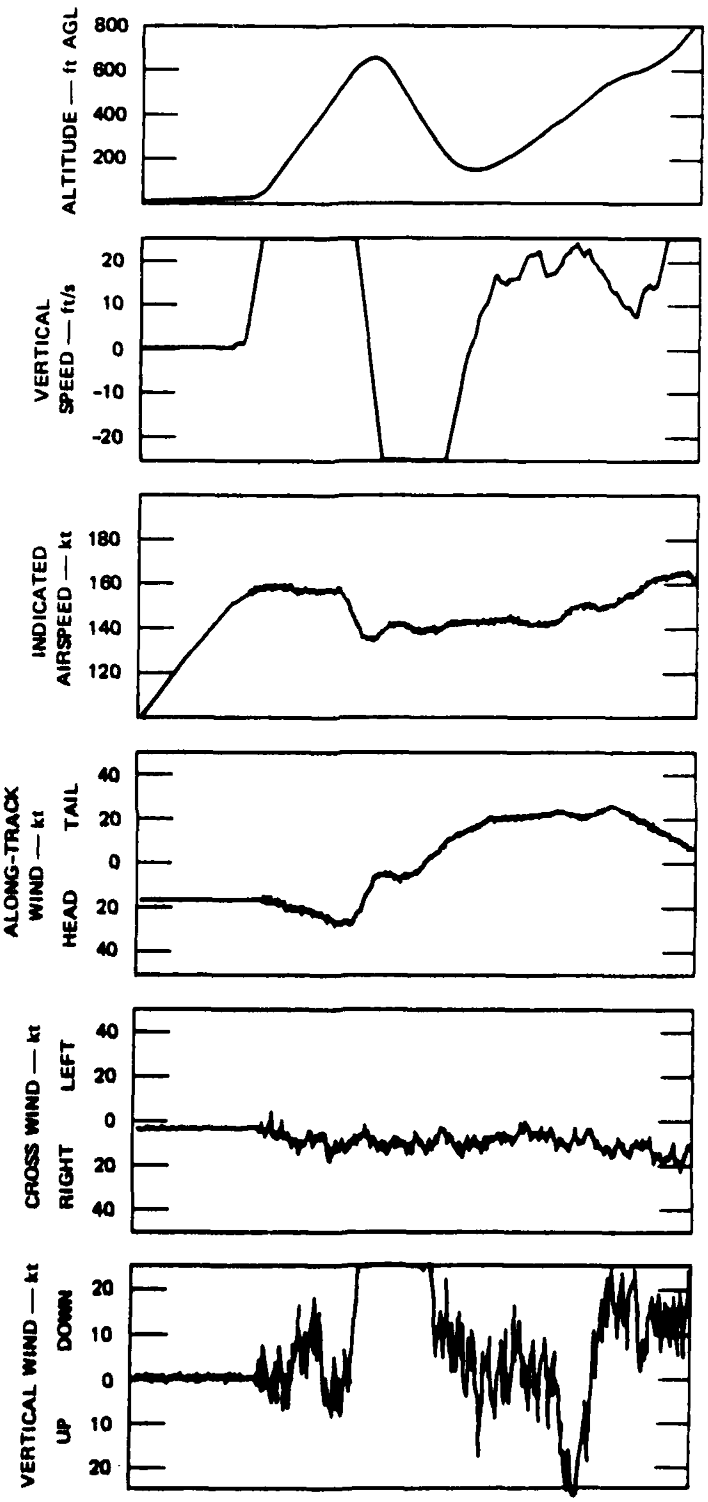


FIGURE 30 TYPICAL AIRCRAFT RESPONSE TO LOW LEVEL WIND SHEAR ON TAKEOFF AND CLIMBOUT

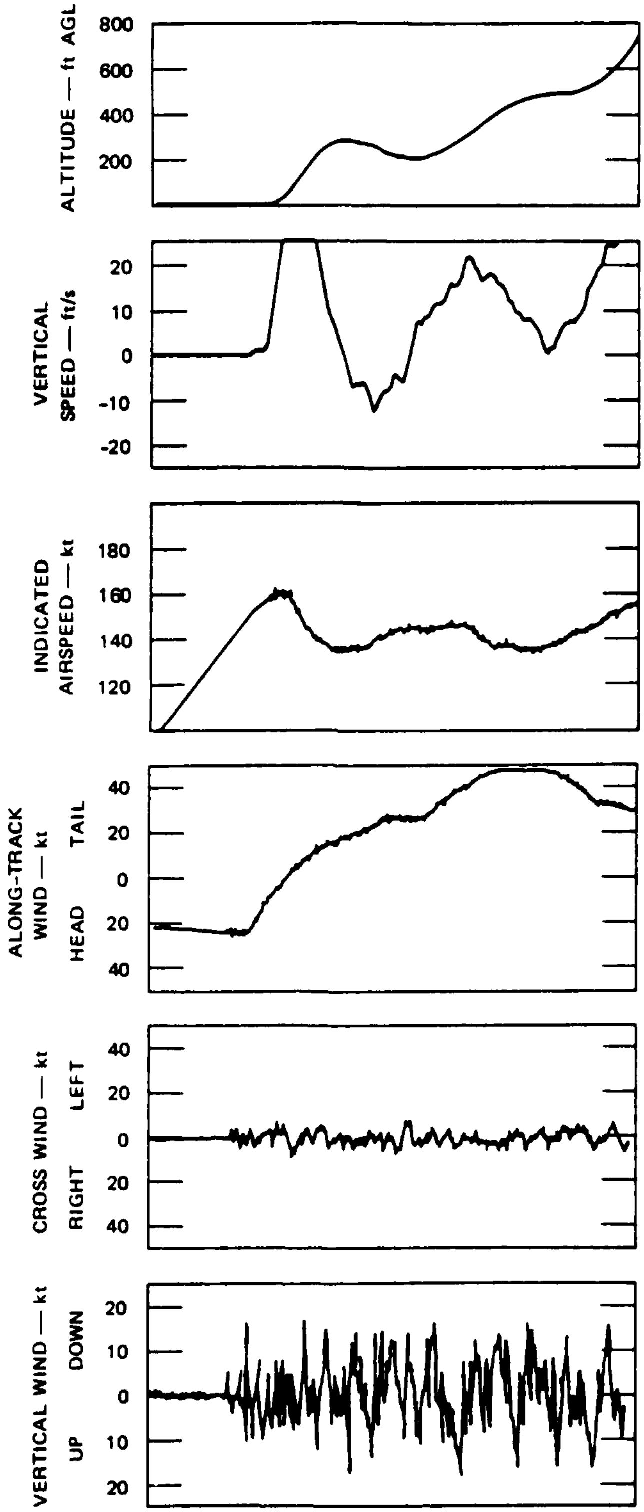


FIGURE 30 (Continued)

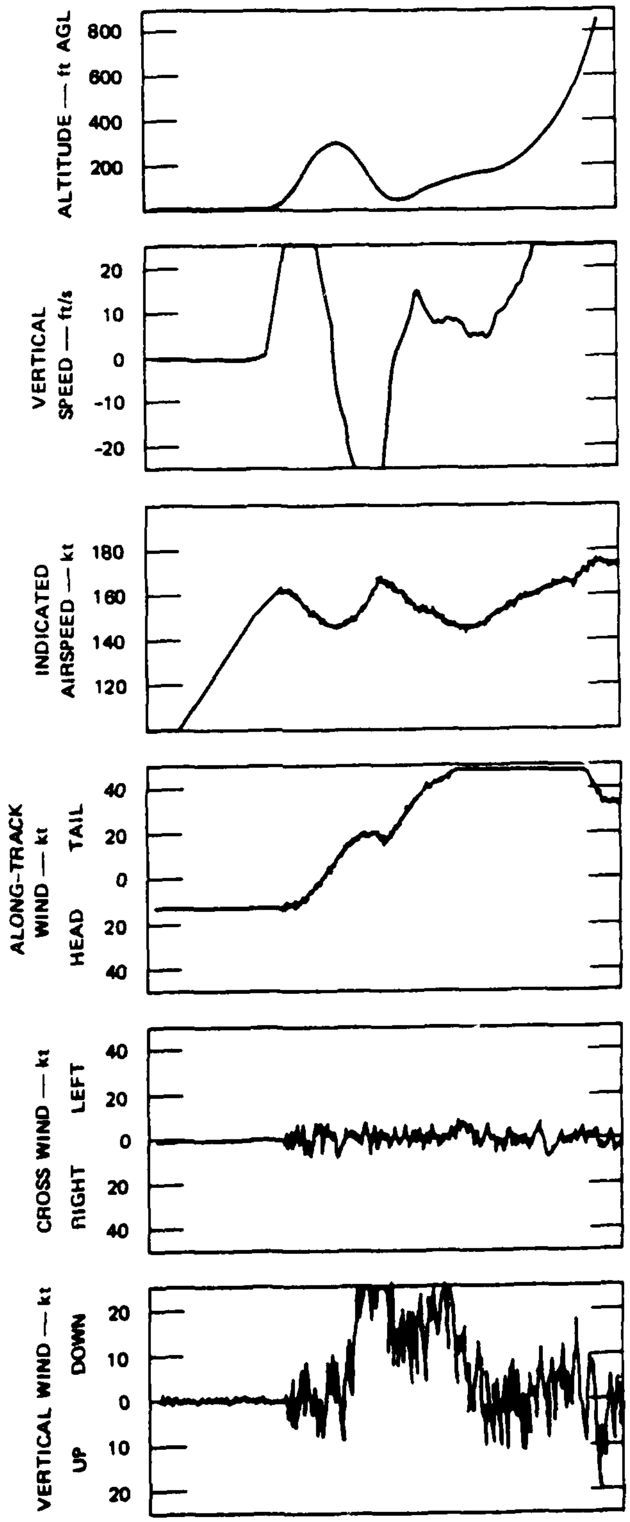


FIGURE 30 (Continued)

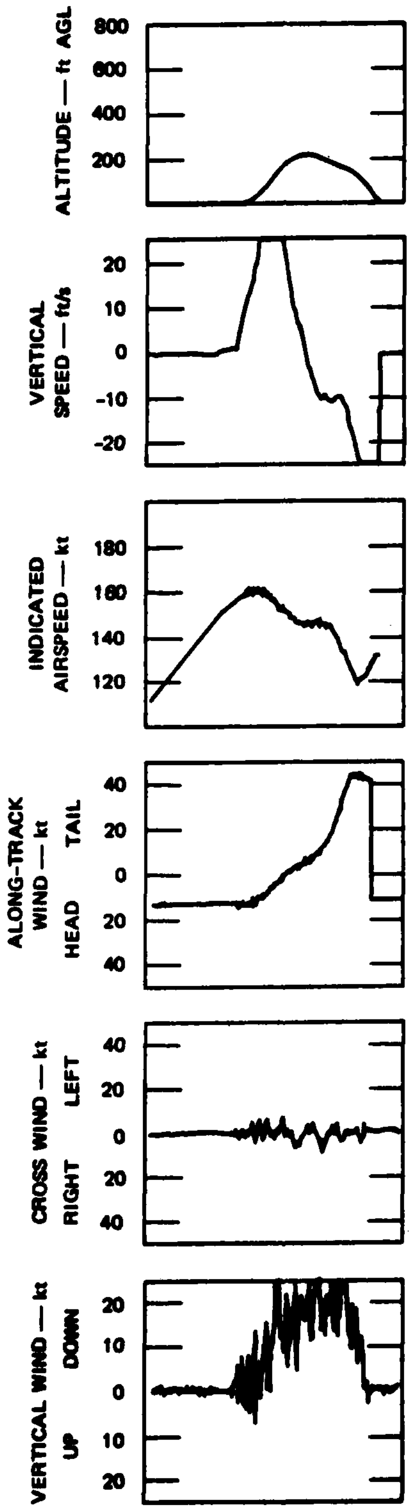


FIGURE 30 (Continued)

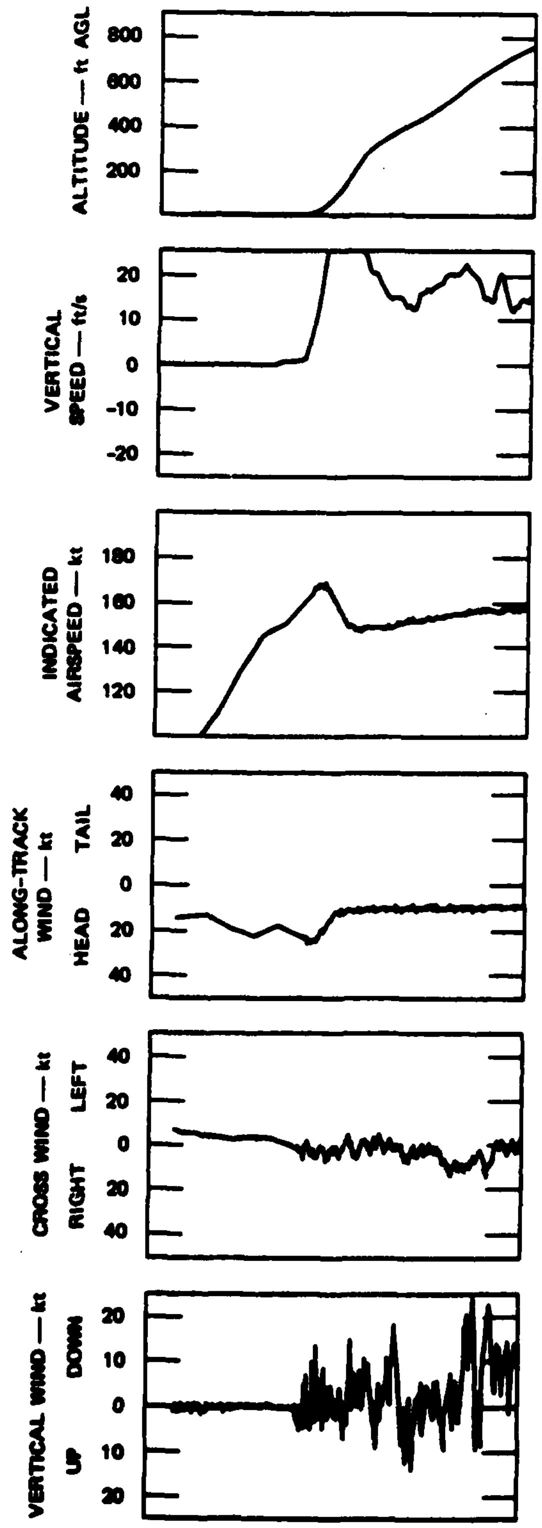


FIGURE 30 (Concluded)

on more than half of the fourth version of this shear (Figure 30a) and on 25% of the third version (Figure 30d). The flights that managed to stay airborne (Figures a, b and c) did so only after substantial altitude loss and a perilously low "recovery." A successful takeoff and climbout, with no loss in altitude, occurred only on the frontal shear (Figure 30e).

Summary data on seven attempted takeoffs against each of the five wind profiles are given in Table 20 for five key flight situation parameters. As expected airspeed loss during the shear encounter corresponded closely to the magnitude of the initial drop in the headwind component. Substantial loss in altitude and high rates of descent occurred on all of the thunderstorm shears. The low altitudes at which positive rates of climb were established after the shear encounter can be considered "recoveries" only where terrain and obstructions in the airport environment would accommodate these maneuvers; in no instance could they be considered operationally safe or acceptable.

Table 20

SUMMARY DATA ON AIRCRAFT RESPONSE TO THE WIND SHEAR ENCOUNTERS FOR SEVEN ATTEMPTED TAKEOFFS

	Wind Profile				
Flight Parameter	WP 11	WP 12	WP 13	WP 14	WP 15
1. Number of Crashes	0	0	2	4	0
2. Mean Airspeed Loss-kt (below V_2 + 10)	28	27	23	33	19
3. Mean Altitude Loss-ft	500	104	240	250	0
4. Mean Recovery Altitude-ft	237	268	67*	143*	N/A
5. Mean Rate of Descent-ft/sec	25	16	25	25	N/A

*n = 5 (2 crashed)
**n = 3 (4 crashed)

V CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions reached by SRI on the basis of the data obtained in this study and outlines our recommendations regarding the subsequent development of the pilot aiding concepts tested. Conclusions are stated with respect to the principal issues addressed in the study, namely:

1) the relative merits of alternative display concepts and computational algorithms for the groundspeed (GNS) and modified flight director (MFD) techniques;
2) the effects of augmenting these techniques with go-around guidance based on acceleration margin (ΔA) and energy rate (ENR) concepts;
3) the level of operational performance and pilot acceptance to be expected when various combinations of GNS, MFD, ΔA, and ENR are available to the pilot for coping with moderate and severe shear encounters; and
4) the hazard represented by an encounter with severe low-level shear during takeoff and climbout.

The conclusions are presented in a series of brief summary statements of the major findings of the study on each of these issues. For an elaboration of these findings, the reader is referred to the more complete representation of supporting data in preceding sections of the report.

A. Conclusions Based on Initial Testing

1. Alternative GNS Display Concepts

a. On the basis of both approach and landing outcomes and pilot evaluations, the two-pointer display of groundspeed combined with the groundspeed control algorithm incorporated in the Fast/Slow indicator (GNS-3) can be considered the best implementation of the speed management technique. Evaluation pilots expressed a clear preference for this

alternative and all of them found it helpful to have the speed management command integrated with the attitude director indicator (ADI).

b. Approach and landing outcomes were as good or better than those recorded for the GNS-3 when the digital display of groundspeed was used without the speed management feature on the Fast/Slow indicator (GNS-5); however, pilot acceptance of this alternative was low.

c. Both approach outcome performance and pilot evaluations were degraded when the Fast/Slow feature was used without a display of groundspeed for cross-checking (GNS-4).

2. <u>Alternative Thrust Commands for the MFD</u>

a. Approach and landing outcomes were substantially better when groundspeed information was incorporated in the thrust command algorithm to compensate for diminishing headwind shear (MFDT-2).

b. Pilot evaluations were the same for both versions of the thrust command and most pilots felt that workload was excessive for both versions.

3. <u>Effects of Adding Go-Around Guidance</u>

a. A substantial increase in the number of go-arounds, relative to baseline conditions (no pilot aiding), occurred when any form of go-around advisory was provided.

b. Based on a logical analysis of approach outcomes (i.e., the Performance Score), the ΔA and ENR concepts were found to produce a substantially greater number of safe outcomes than either the baseline or modified baseline (First Officer callouts) procedures.

c. False or suspect advisories occurred on a third of the approach sequences when either the ΔA or ENR techniques was used with baseline approach management techniques; false and suspect advisories were lowest when the ENR advisories were paired with the MFDT-2 technique.

d. No clear preferences or endorsements of the ΔA or ENR concepts were expressed by the evaluation pilots, but pilots did prefer

the scale pointer display that showed ENR trends over the digital display used for ΔA.

B. Conclusions Based on Full-Scale Testing

1. Projected Operational Performance

The most pertinent measures of performance for the Full Trial were the approach-and-landing outcome data. Past simulation exercises have shown that a rate of 91 percent in-limits landings can be expected in comparable simulated conditions with no wind shear, so we take this to be the standard of acceptance for the tests with wind shear. Over all 4 test wind profiles and counting both in-limits landings and successful go-arounds, the systems GNS-3/ENR, with 91.5%, and MFDT-2/ENR, with 91.1% would have met this standard if all the system-generated go-around advisories had been honored; system GNS-6/ΔA was close with 86.5%. This level was not attained because in some runs the pilots did not notice or chose to ignore the advisory, so it represents potential performance. The actual counts of in-limits landings and successful go-arounds were lower than the standard, being 73.6% for GNS-3/ENR, 72.1% for GNS-6/ΔA, and 71.3% for MFDT-2/ENR. The difference between potential and actual performance emphasizes the need for an effective go-around decision aid in coping with wind shear on approach and landing.

Appropriate responses to the shears of moderate severity were quite different from those to high-severity shears. System MFDT-2/ENR was best of the three on the moderate profiles, with 70.0% in-limits landings, 8.0% go-arounds, and a potential of 92.0% success. On the high-severity profiles system GNS-3/ENR was best with 16.7% in-limits landings, 62.5% go-arounds and a potential success level of 100%. The better success rate on high-severity shears was probably due to the go-around advisories being more consistent with the pilot assessment.

The incidence of false alarms for the go-around advisories was high. GNS-3 and GNS-6 showed better speed management (airspeed and groundspeed), while MFDT-2 showed better lateral tracking. Workload ratings were about the same. Taking all measures into consideration, there seems to be little to choose between the three systems.

2. Pilot Acceptance

a. Subject pilots expressed a high degree of confidence in their potential ability to handle actual low-level shear encounters for all three of the aiding configurations tested. As in earlier testing, the pilots preferred the two-pointer display of groundspeed over the digital readout and most of them were critical of the excessive activity of the MFD steering commands.

b. The ENR concept was preferred over the ΔA concept for the go-around advisory, primarily because it provided trend information on the effects of the shear. The ΔA information was considered to be more useful for anticipating the need for a go-around, but most pilots wanted to see the trend developing rather than wait until the acceleration margin had reached a critical level.

c. The MFD was preferred over the standard flight director by more than two-thirds of the pilots and most of them felt that they could do a better job of glide slope tracking using the MFD. The incorporation of the groundspeed management algorithm into the Fast/Slow indicator was highly regarded by all of the pilots and judged by them as very effective in maintaining both indicated airspeed and groundspeed minimums.

3. The Takeoff Hazard

a. Low-level encounters with severe thunderstorm shears, characterized by substantial headwind shearout and downdrafts in excess of 10 knots, are extremely hazardous. Crashes were recorded on more than half of the takeoffs attempted under this condition and flights that managed to stay airborne did so only after substantial loss of altitude.

b. Successful takeoff and climbout was recorded for a frontal shear with a 15 knot headwind shearout accompanied by a steady downdraft component of approximately 5 knots.

C. Recommendations

These tests emphasize the differences between moderate- and high-severity shears in the problems they present to the pilot. With a moderate

shear, a majority of pilots can land in limits when provided with effective path-tracking and speed-management aids. On high-severity shears, such as the two test profiles (#4 like Allegheny/Philadelphia and #10 like Eastern/J. F. Kennedy) of the Full Trial, it is physically possible to land the aircraft in limits but the most appropriate action probably is to execute a go-around. It follows that a system for coping with low-level shear requires both effective approach management and a useful go-around decision aid.

It is clear that integration of the appropriate signals into the drive commands for the normal flight-director steering bars and Fast/Slow indicator is the most natural and effective way to aid the pilot in approach management. Examples are the acceleration augmentation of the steering and Fast/Slow commands of MFDT-2, and the use of groundspeed information in all three systems of the Full Trial. Results of the Initial Trial indicate, however, that this integration technique may not be sufficient. There it was noted, in the groundspeed experiment, that the pilot should have backup information to verify the aircraft state and to provide some assurance that the Fast/Slow command was appropriate.

Backup information is particularly important in support of any go-around decision aid or advisory. This was emphasized in the Full Trial, where the GNS-6/ΔA system provided only a warning light to advise go-around. While the outcome performance level was comparable to that of the other two systems, the subject pilots expressed strong opposition to having only the light without some information to show why the light had turned on. It was noted that pilots in actual operations will be reluctant to accept and act on a go-around advisory when the other displays seem to indicate that the approach is within acceptable limits. When cross-checks of the conventional instruments did confirm the go-around warning it was often too late to execute a successful missed-approach. Therefore, a go-around advisory or wind shear warning should not only be issued in an on-off fashion but also should be supported by a display of the reason for the warning and an analog display of information that will enable the pilot to see a trend toward a hazardous state. The instruments

in current conventional use (e.g., the "baseline" DC-10 instrumentation) do not supply all the information needed.

Our primary recommendation, then, is for additional study and development of the go-around guidance problem. Refinements to both the computational algorithms for generating wind shear warnings and the display of these alerts and supportive flight situation data are needed to enhance their effectiveness and assure pilot acceptance and correct usage. It may also be necessary to develop special demonstrations or confidence building exercises so that pilots will more fully appreciate the predictive character of the shear alerts and the need for a timely response.

The development effort leading up to these DC-10 advanced tests has emphasized approach management, considering both acceleration augmentation and use of groundspeed information. The results of the Initial Trial showed that groundspeed is particularly important; it was needed in all systems selected for the Full Trial. The three systems differed in their steering algorithms (baseline DC-10 or Collins acceleration augmentation) and their speed commands (groundspeed error or Collins modification with headwind shear compensation), but their performance was comparable. This suggests that several potential solutions to the wind shear problem are available. Also, it would appear that further development of precision approach management aids is not needed. The tests indicate that all three systems, with improvement of go-around decision aids, have the potential to provide an adequate level of performance in wind shear.

A major issue requiring further study is the need for improved guidance for executing the go-around maneuver or takeoff and climbout through the shear when the aircraft must operate as close as possible to aerodynamic limits. Even with timely initiation of the go-around, the pilot will have to fly through the shear and it may be necessary to fly at optimum angle-of-attack, and close to stall speeds, in order to minimize altitude loss and achieve a positive rate of climb. Standard flight director pitch steering commands for the go-around mode and standard procedures for takeoff and climbout may not produce maximum climb capability for coping with severe low-level shear conditions.

APPENDIX A

Description of Wind Shear Profiles

Table A-1 summarizes the wind profiles selected for use in the DC-10 piloted simulator tests on wind shear. Each wind profile includes mean wind and turbulence specifications. Figures A-1 through A-10 show the mean wind components, as encountered on a 3-degree glide slope, for the approach wind profiles listed in Table A-1. The takeoff wind profile wind components, as encountered on a 6-degree departure path, are shown in Figures A-11 through A-15.

1. Mean Wind Specification

Each wind profile includes three wind components specified as a function of both altitude and distance along track. Each component is specified as a table lookup function with up to 21 altitude values and up to 16 distance values with straight-line interpolation between points. The altitude points are not equally spaced nor are they the same for each wind profile, although they are the same over all distance values of a given profile. The maximum amount of storage required for the mean wind values is 3 x 21 x 16 = 1008 points.

2. Turbulence Specification

Turbulence parameters are included with each wind shear profile. Six parameters (3 rms intensities and 3 scale lengths) are each specified as a function of altitude using a table lookup function with up to 21 altitude values. The maximum amount of storage required for the turbulence associated with a wind profile is 6 x 21 = 126 points. This brings the maximum total storage for a wind profile with turbulence to 1008 + 126 = 1134 points.

The turbulence models used are developed from the Dryden spectra.[8] Turbulence wind components are generated by feeding a random, white,

zero-mean, unit-variance input into a filter F(s). Transfer functions are as follows:

Longitudinal $$F_u(s) = \sigma_u \sqrt{\frac{L_u}{\pi V_a}} \frac{1}{1 + \frac{L_v}{V_a}s} \;;$$

Lateral $$F_v(s) = \sigma_v \sqrt{\frac{L_v}{2\pi V_a}} \frac{1 + \sqrt{3}\frac{L_v}{V_a}s}{\left(1 + \frac{L_v}{V_a}s\right)^2} \;;$$

Vertical $$F_w(s) = \sigma_w \sqrt{\frac{L_w}{2\pi V_a}} \frac{1 + \sqrt{3}\frac{L_w}{V_a}s}{\left(1 + \frac{L_w}{V_a}s\right)^2} \;;$$

where: $\sigma_u, \sigma_v, \sigma_w$ = rms intensities

L_u, L_v, L_w = scale lengths

V_a = true airspeed

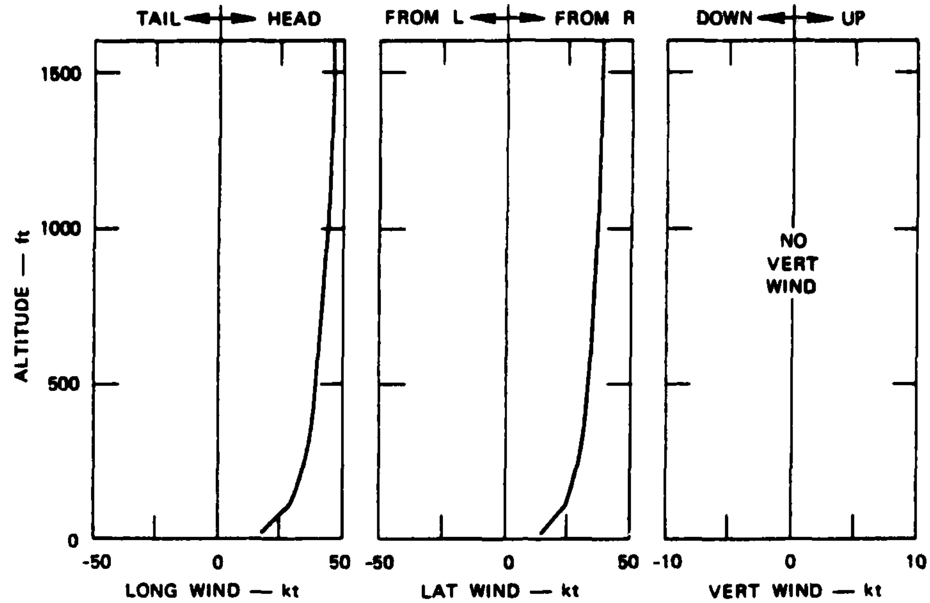
s = Laplace transform variable.

Table A-1

SUMMARY OF WIND PROFILES USED IN PILOTED SIMULATIONS

Relative Wind Profile Severity	Source of Wind Data	Meteorological Wind Data	DC-10 Simulator Tests, Wind Profile No.
Approach			
Low	Meteorological math model	Neutral	1
Moderate	Logan accident reconstruction	Warm front	5
	Tower measurements	Thunderstorm	7
	Tower measurements	Thunderstorm	8
	Tokyo accident reconstruction	Warm front	2
High	Tower measurements	Cold front	9
	Kennedy accident reconstruction	Thunderstorm	6
	Kennedy accident reconstruction	Thunderstorm	10
	Philadelphia accident reconstruction	Thunderstorm	4
	Mathematical model	Thunderstorm	3
Takeoff			
	Kennedy accident reconstruction	Thunderstorm	11
	Philadelphia accident reconstruction	Thunderstorm	12
	Philadelphia accident reconstruction	Thunderstorm	13
	Philadelphia accident reconstruction	Thunderstorm	14
	Tower measurements	Cold front	15

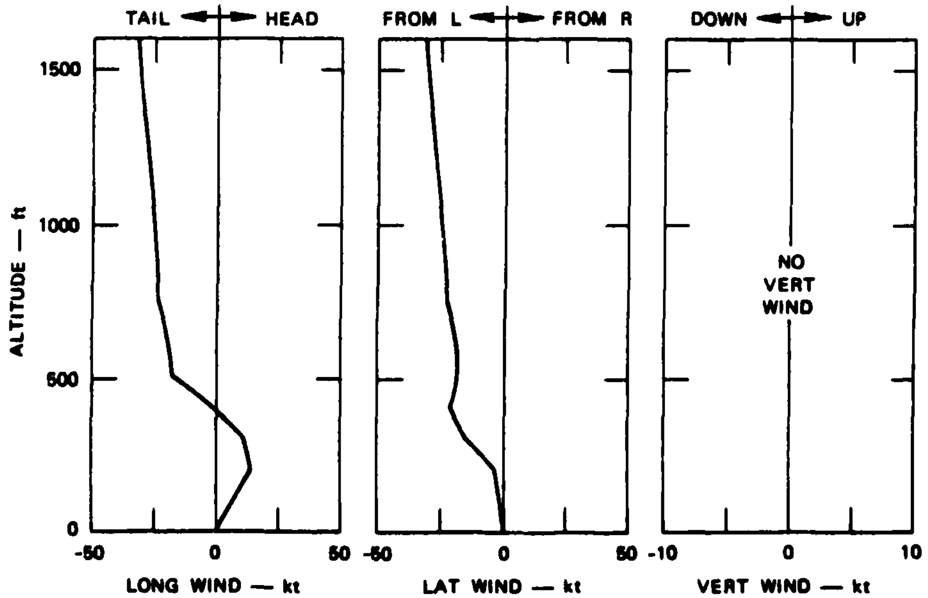
Profile Severity: Low
Meteorological Type: Neutral



Source: Meteorological math model

FIGURE A-1 WIND PROFILE 1, APPROACH ON 3° GLIDE PATH

Profile Severity: Moderate
Meteorological Type: Warm front



Source: Logan accident (1973) reconstruction

FIGURE A-2 WIND PROFILE 5, APPROACH ON 3° GLIDE PATH

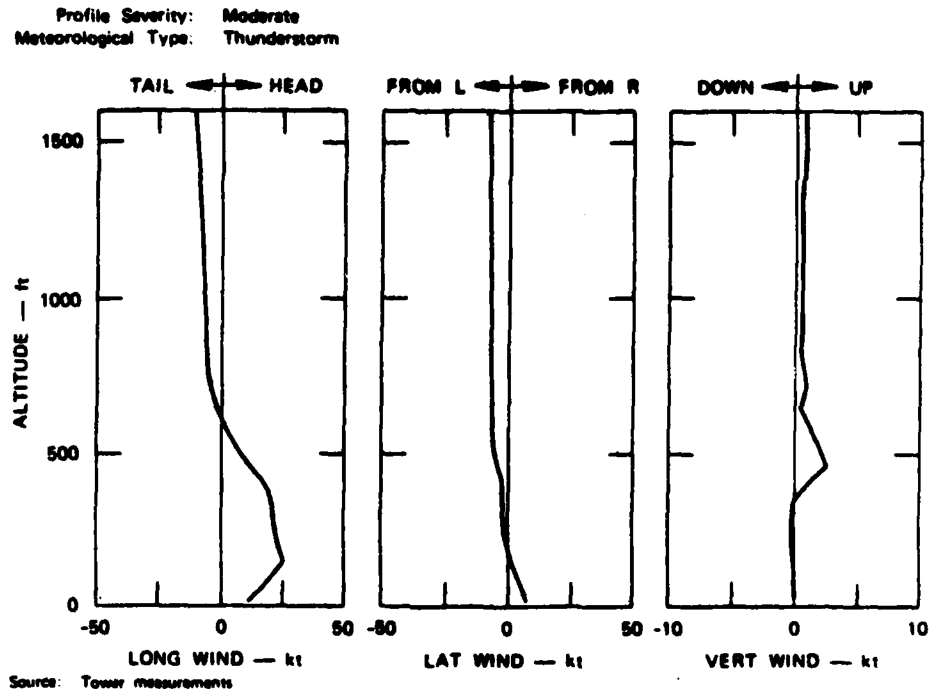


FIGURE A-3 WIND PROFILE 7, APPROACH ON 3° GLIDE PATH

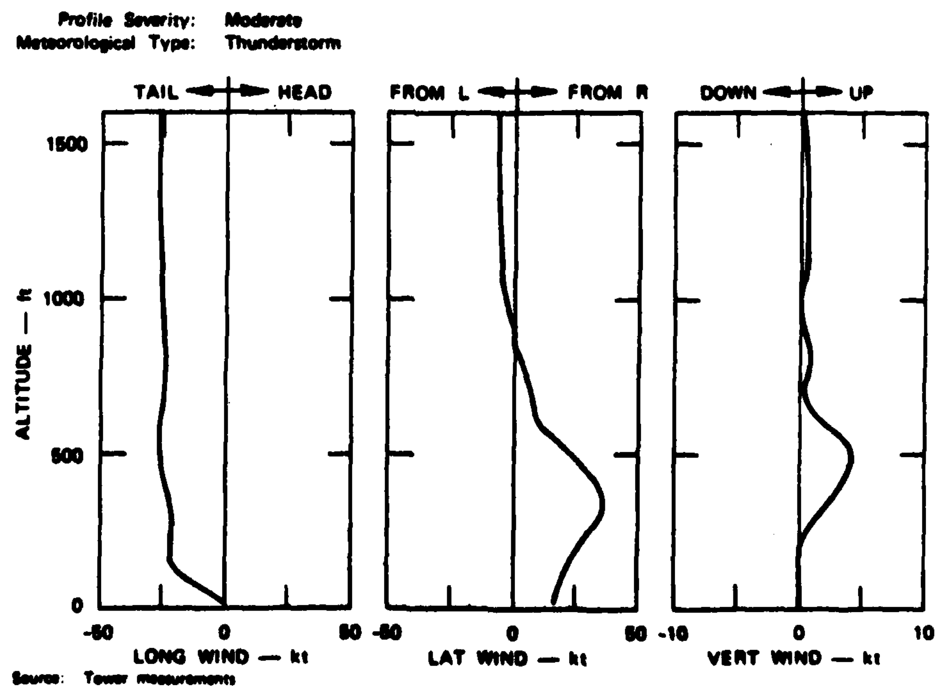
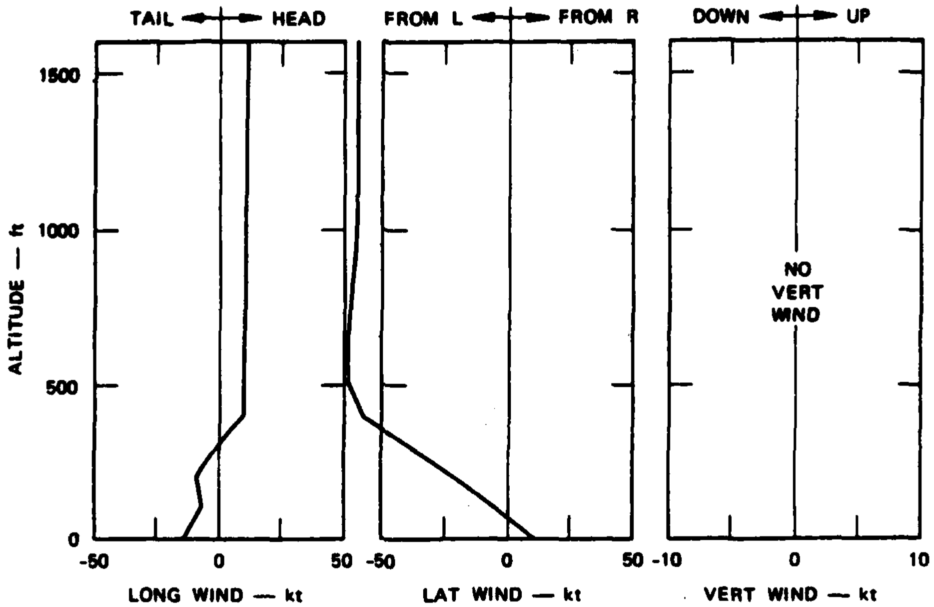


FIGURE A-4 WIND PROFILE 8, APPROACH ON 3° GLIDE PATH

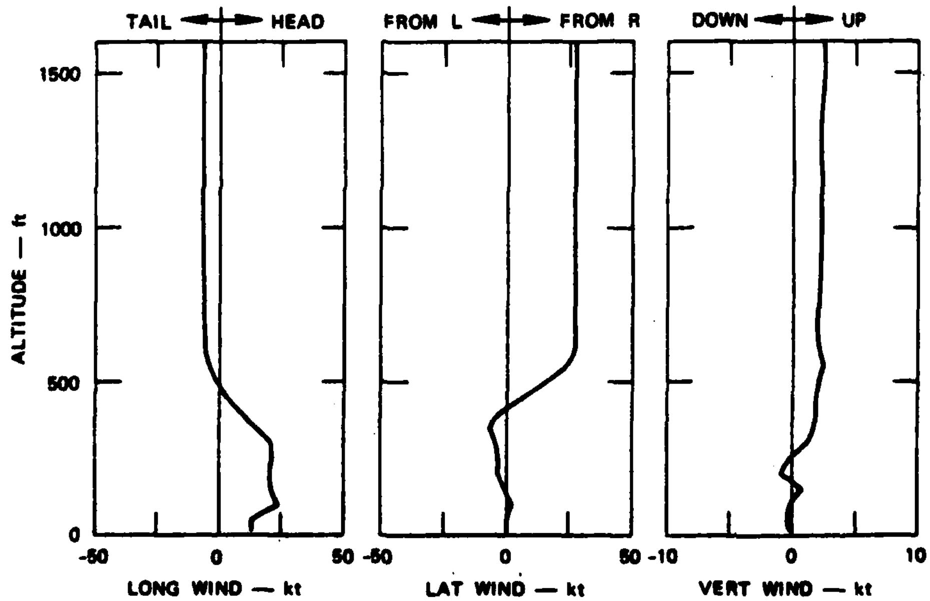
Profile Severity: Moderate
Meteorological Type: Warm Front



Source: Tokyo (1966) accident reconstruction

FIGURE A-5 WIND PROFILE 2, APPROACH ON 3° GLIDE PATH

Profile Severity: High
Meteorological Type: Cold Front



Source: Tower measurements

FIGURE A-6 WIND PROFILE 9, APPROACH ON 3° GLIDE PATH

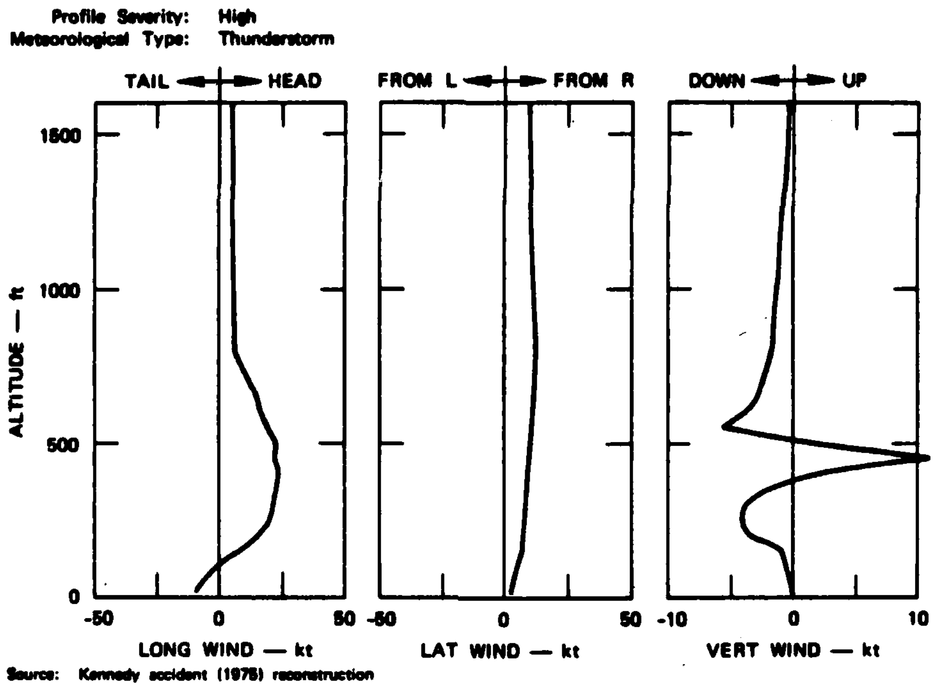


FIGURE A-7 WIND PROFILE 6, APPROACH ON 3° GLIDE PATH

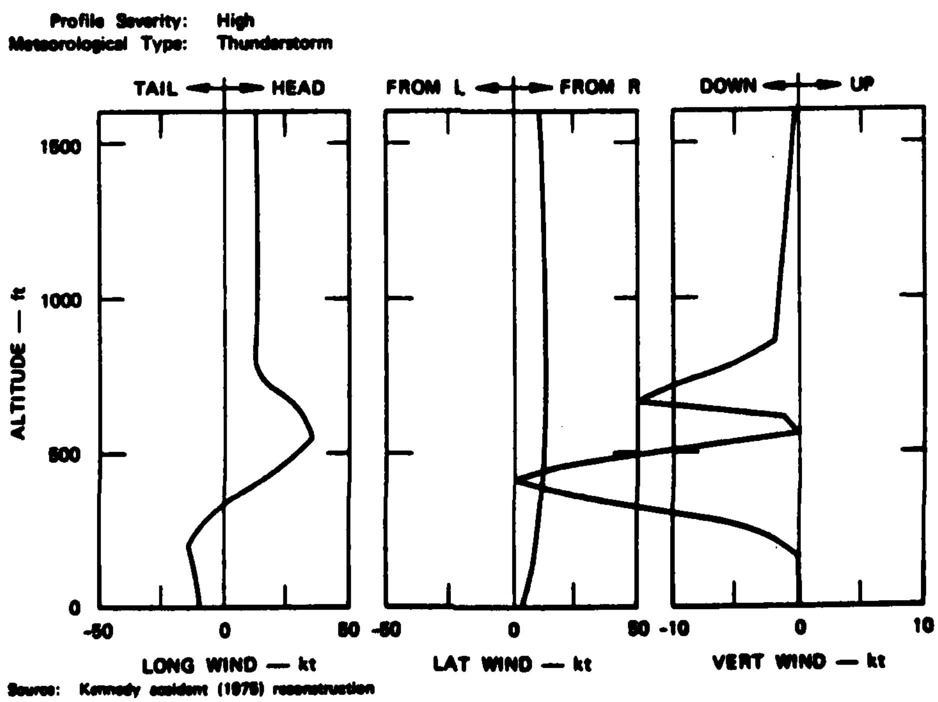
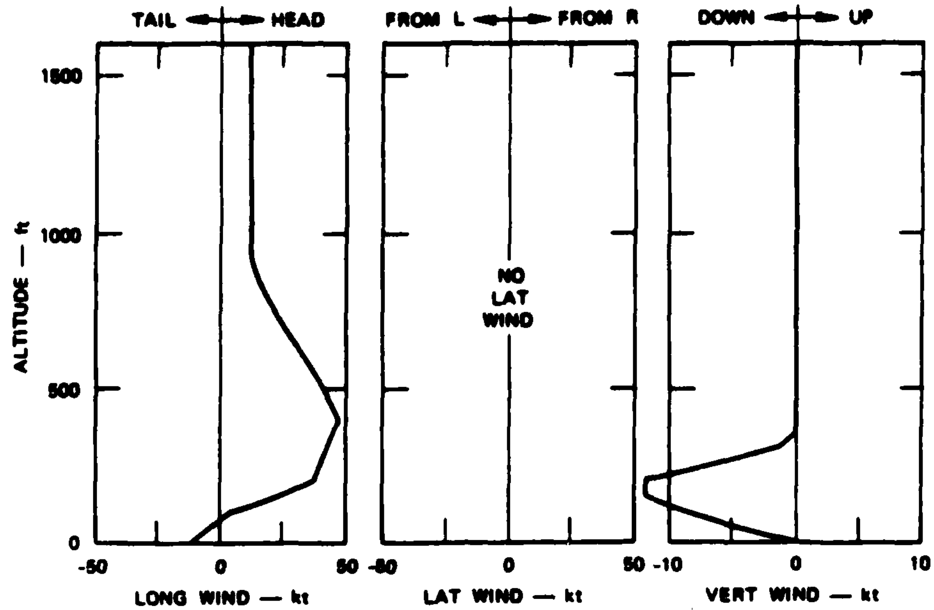


FIGURE A-8 WIND PROFILE 10, APPROACH ON 3° GLIDE PATH

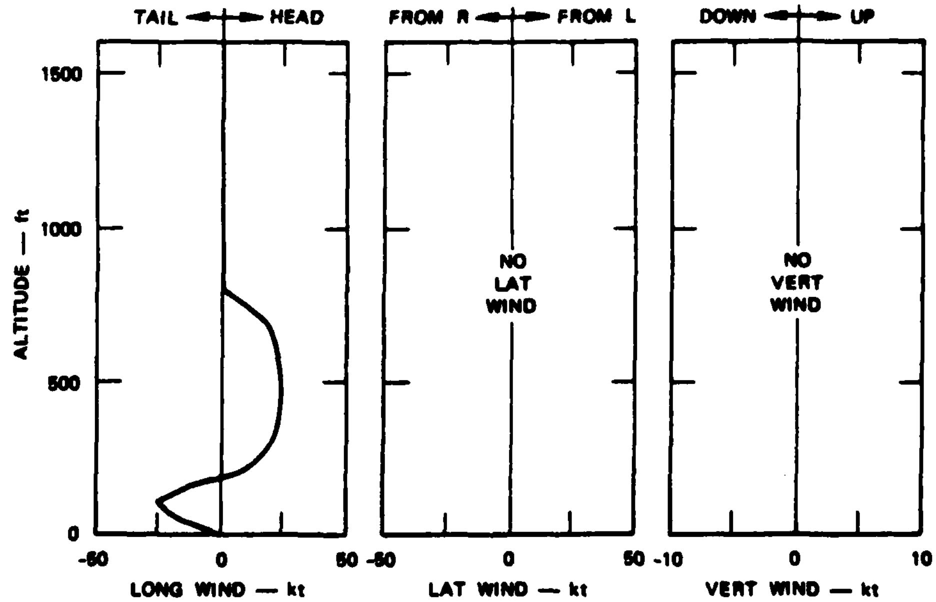
Profile Severity: High
Meteorological Type: Thunderstorm



Source: Philadelphia accident (1976) reconstruction

FIGURE A-9 WIND PROFILE 4, APPROACH ON 3° GLIDE PATH

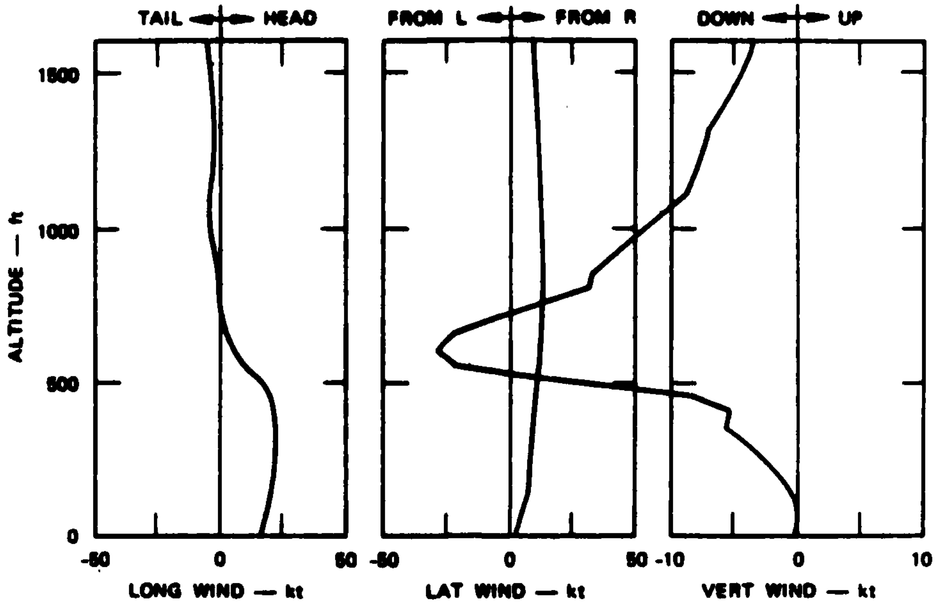
Profile Severity: High
Meteorological Type: Thunderstorm



Source: FAA Hazard Definition Study

FIGURE A-10 WIND PROFILE 3, APPROACH ON 3° GLIDE PATH

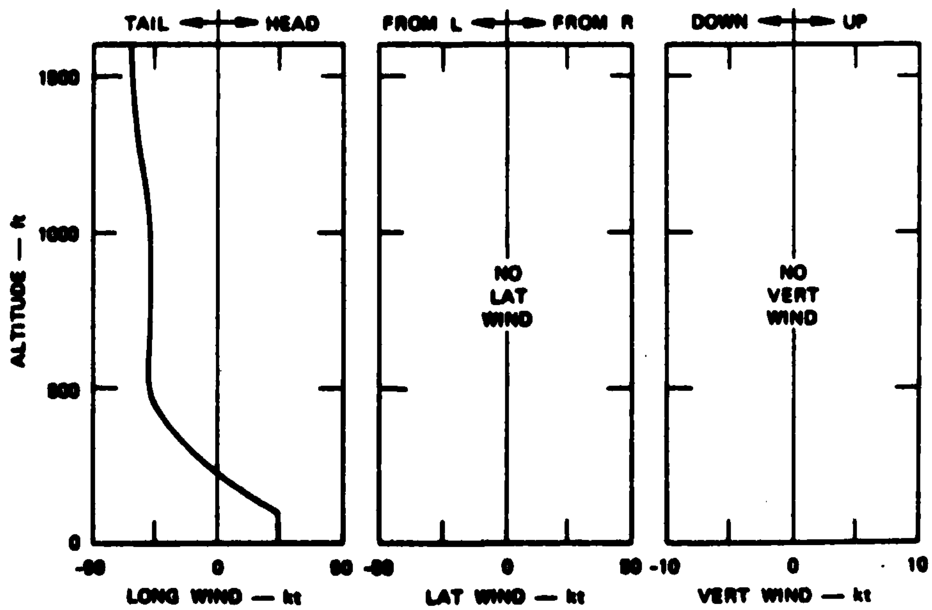
Meteorological Type: Thunderstorm



Source: Kennedy accident (1975) reconstruction

FIGURE A-11 WIND PROFILE 11, TAKEOFF WITH 6° CLIMBOUT

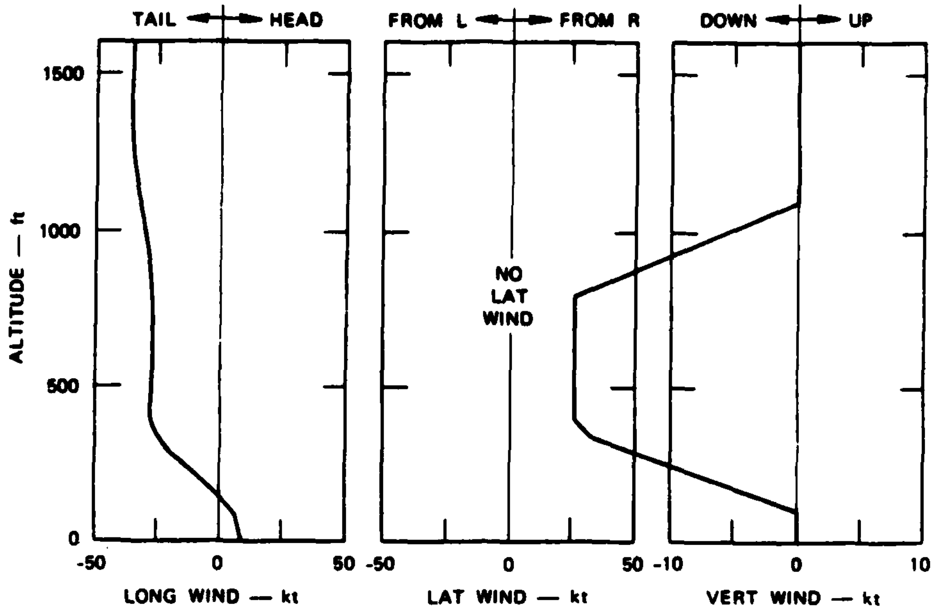
Meteorological Type: Thunderstorm



Source: Philadelphia accident (1976) reconstruction

FIGURE A-12 WIND PROFILE 12, TAKEOFF WITH 6° CLIMBOUT

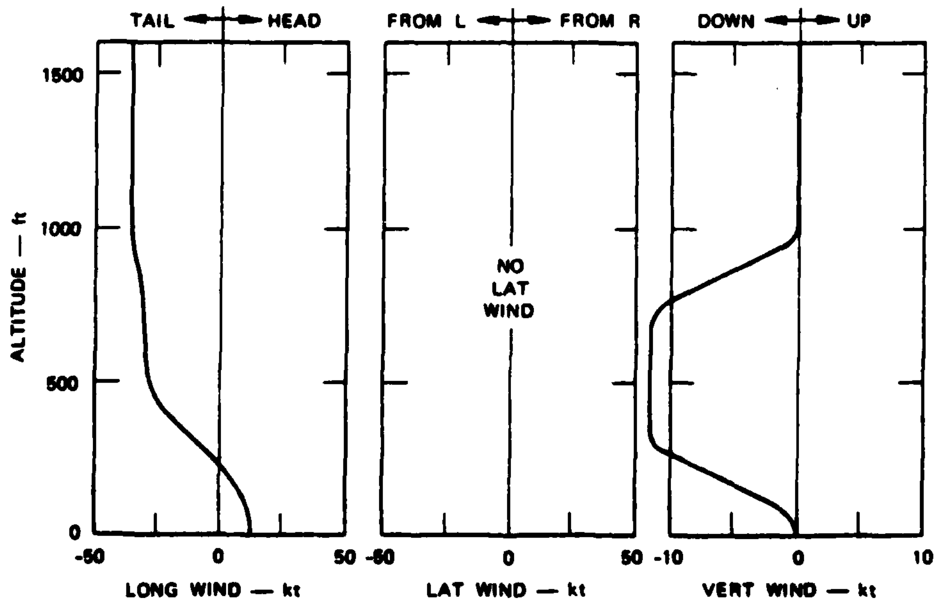
Meteorological Type: Thunderstorm



Source: Philadelphia accident (1976) reconstruction

FIGURE A-13 WIND PROFILE 13, TAKEOFF WITH 6° CLIMBOUT

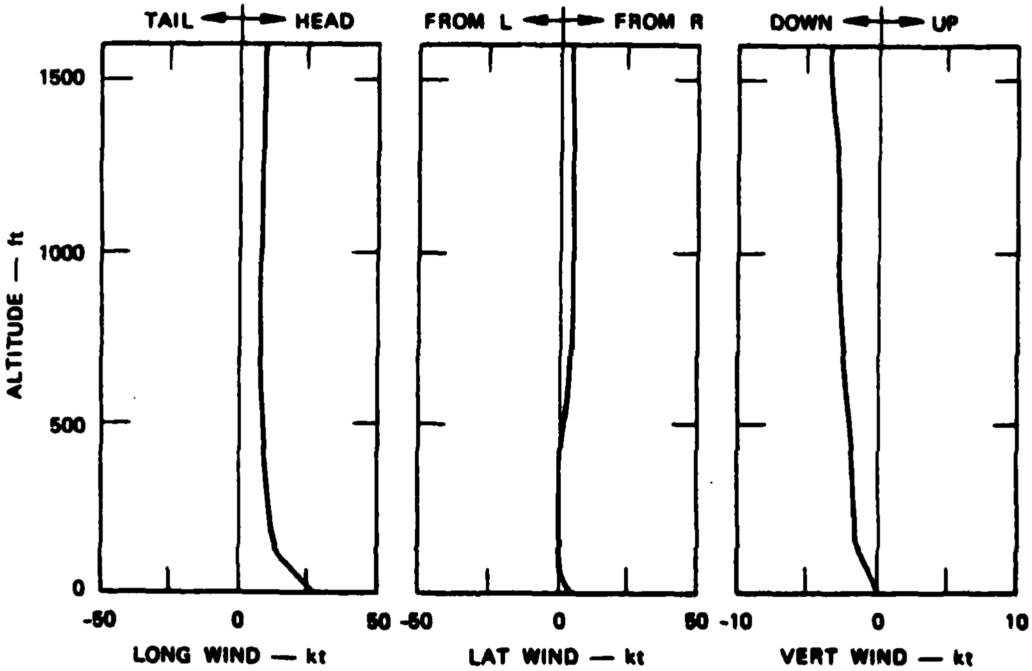
Meteorological Type: Thunderstorm



Source: Philadelphia accident (1976) reconstruction

FIGURE A-14 WIND PROFILE 14, TAKEOFF WITH 6° CLIMBOUT

Meteorological Type: Cold Front



Source: Tower measurements

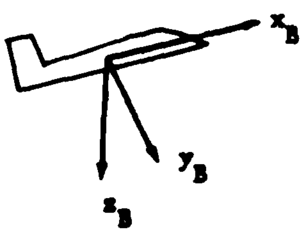
FIGURE A-15 WIND PROFILE 15, TAKEOFF WITH 6° CLIMBOUT

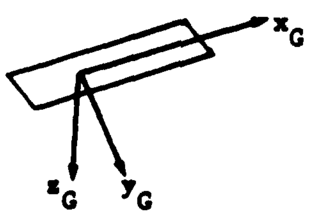
APPENDIX B

On-Site Data Recording

This appendix lists the flight situation and aircraft state parameters that were recorded on magnetic tape and strip charts during each simulated approach and landing sequence. A brief description of the data elements available on the summary data printout for each run is also provided.

The coordinate system adopted for representing these parameters in the simulation is as follows: the ground-axis system consists of a right-handed orthogonal axis whose origin is attached to the surface of the earth at the intersection of the glide path and the centerline of the runway. As illustrated below, the x_G axis is coincident with the runway centerline and is positive in the direction of the departure end of the runway. The z_G axis points vertically along the g vector and is positive downward. The body-axis system consists of right-handed, orthogonal axes whose origin is fixed at the nominal aircraft center of gravity. Its o. .entation remains fixed with respect to the aircraft, with the x_B axis taken along the body centerline (positive forward) and the $_B$ axis taken outward from the belly of the aircraft in the plane of symmetry. The y_B axis is then positive out the right wing.





1. Data Recorded on Magnetic Tape

The digitally logged data were recorded on 9-track 800 BPI digital magnetic tape. The characteristics of the sampling process were as follows:

a.) Sampling rate was 5 Hz.

b.) Each parameter was represented as a scaled 16-bit 2's complement number. In the event of an overflow the number will be clipped at either $2^{15} - 1$ (positive) or 2^{15} (negative).

c.) A frame consisted of the 40 parameters listed in Table B-1.

Table B-1

FLIGHT SITUATION PARAMETERS RECORDED ON MAGNETIC TAPE

Number	Symbol	Description	Engineering Units
1	t	Time code, elapsed time from initiation of run	.050 sec
2	X	Position coordinates as measured to the	ft
3	Y	aircraft center of gravity, ground-axis	ft
4	Z	referenced	ft
5	Ψ_e	Heading angle referenced to the runway heading (positive right of runway heading on approach)	deg
6	θ	Pitch angle (positive nose up)	deg
7	α	Angle of attack (pitch angle minus air referenced flight path angle)	deg
8	φ	Roll angle (positive right wing down)	deg
9	$\dot{X}$	Ground reference velocities, the rate	ft/sec
10	$\dot{Y}$	of change of x, y and z components	ft/sec
11	$\dot{Z}$		ft/sec
12	A_x	Longitudinal acceleration along the x-body axis at the center of gravity (positive forward)	ft/sec^2
13	A_n	Normal acceleration parallel to the z-body axis at the center of gravity	ft/sec^2

Table B-1

FLIGHT SITUATION PARAMETERS RECORDED ON MAGNETIC TAPE (con't)

Number	Symbol	Description	Engineering Units
14	p	Pitch rate, angular velocity about y-body axis (positive nose up)	deg/sec
15	q	Roll rate, angular velocity about x-body axis (positive right wing down)	deg/sec
16	r	Yaw rate, angular velocity about z-body (positive nose right)	deg/sec
17	W_x	Wind velocity, ground-axis referenced x, y and z components	knots
18	W_y		knots
19	W_z		knots
20	IAS	Indicated airspeed as displayed	knots
21	GNS	Groundspeed after computation as displayed	knots
22	PSB	Pitch and bank steering bars and speed command as displayed on the pilot's ADI	bar widths
23	BSB		bar widths
24	SC		knots
25	LOC	Localizer and glide slope deviation as displayed	dots
26	GS		dots
27	ENR	Energy rate as displayed	to be defined
28		not used	
29	N_1	Engine RPM N_1 of the center engine	%
30	Δ_A	Acceleration margin	ft/sec^2
31	δ_{TH}	Position of the center engine throttle lever	deg
32	δ_F	Flap position	deg
33	V_{APP}	Approach airspeed	knots
34	δ_e	Elevator position	deg
35	i_h	Stabilizer angle	deg
36	δ_r	Rudder deflection	deg
37	δ_a	Aileron deflection	deg
38	δ_w	Control wheel position	deg
39	δ_c	Control column position	deg
40		This 16-bit word was reserved for the following binary events:	

Bit No.	Description
0 (MSB)	Spare
1-5	Spare
6	Spare
7	Stall warning
8	Outer marker
9	Middle marker
10	Inner marker
11	Trim up
12	Trim down
13	Landing gear down
14	Main gear touchdown
15	Go-around initiation, true, when pilot or first officer button pushed

2. Strip Chart Recording

Sixteen channels of analog data are required. The recorded parameters are listed in Table B-2.

Table B-2

FLIGHT SITUATION PARAMETERS RECORDED ON STRIP CHARTS

Parameter	Symbol	Unit	Range
1. Range	R	nm	-0.5 to 4.5
2. Vertical height	H	ft	0 to 1000
3. Localizer deviation (positive right of path)	LOC	dots	$\pm$ 2.5
4. Glide slope deviation (positive above glide path)	GS	dots	$\pm$ 2.5
5. Vertical speed	$\dot{H}$	ft/s	$\pm$ 25.0
6. Indicated airspeed	IAS	kt	50 to 250
7. Groundspeed	GNS	kt	50 to 250
8. RPM (center engine)	N_1	%	10 to 110
9. Vertical height	(same as 2 above, repeated on strip chart 2)		
10. Along-track wind component	W_x	kt	$\pm$ 50
11. Cross-track wind component	W_y	kt	$\pm$ 50
12. Vertical wind component	W_z	kt	$\pm$ 50

Table B-2

FLIGHT SITUATION PARAMETERS RECORDED ON STRIP CHARTS (con't)

Parameter	Symbol	Unit	Range
13. Acceleration margin	Δ_A	ft/sec^2	$\pm$ 50
14. Command airspeed	SC	kt	50 to 250
15. Energy rate	ENR	to be defined	
16. Angle of attack	α	deg	-15 o 35

3. Summary Data Printout

The data content and format of the summary data printout is illustrated in Figure 3 in Section II of this report. Table B-3 provides a brief description of each data entry on this printout.

Table B-3

DATA ENTRIES OF THE SUMMARY PRINTOUT

Entry	Description	Units
1. DATE	Calendar day, month, and year, each separated by a dash	day, mo, yr
2. SUBJECT	Subject pilot, entered via the control box at the instructor's station	integer
3. V(REF)	Reference airspeed, sampled at 800 ft GS altitude (1.3 V_S, with V_S a function of weight and flap setting)	knots
4. TIME	Clock time at run initiation, using hours, minutes and seconds	hr, min, s
5. DISPLAY	Identifies test display, entered via the control box at the instructor's station	integer
6. V(APP)	Target approach airspeed, as selected by the pilot; sampled at 800 ft GS altitude (V_{REF} + additives)	knots
7. RUN NO	The master run number, entered via the control box at the instructor's station	integer
8. WIND PRO	Identifies the selected wind profile, entered via the control box at the instructor's station	integer

Table B-3

DATA ENTRIES OF THE SUMMARY PRINTOUT (con't)

Entry		Description	Units
9.	GNS(REF)	Reference groundspeed, sampled at 800 ft GS altitude. $GNS_{REF} = V_{REF} + W_{x20}$, where W_{x20} is the X-component of wind at 20 ft height above runway in ground-axis coordinates, i.e., head winds have negative signs; for a tail-wind, GNS_{REF} is greater than V_{REF}.	knots
10.	RUN VL	Run validity, with 0 indicating an invalid run	integer
11.	GS ALT	Glide slope altitude (-X tan 3^{o})	ft
12.	DIST	Aircraft's along-track position	nm
13.	VERT OFFSET	Aircraft's vertical displacement from the glide path (positive above glide path)	ft
14.	LAT OFFSET	Aircraft's lateral displacement from the extended runway centerline	ft
15.	VERT SPEED	Vertical speed	ft/min
16.	LAT SPEED	Ground referenced cross-track velocity	ft/min
17.	GROUNDSPEED	Groundspeed, as displayed	kt
18.	AIRSPEED	Indicated airspeed	kt
19.	LIMIT	Approach outcome and touchdown limits, with 1 indicating aircraft is within flight path offset and velocity limits, and 0 indicating outside limits	integer
20.	ENERGY RATE	Energy rate as displayed and computed per Douglas specification	to be defined
21.	ACCEL MARGIN	Acceleration margin	ft/sec^2
22.	TD	Parameters 12 through 21 are printed out at touchdown	
23.	G/A	Same as 22 for a go-around	
24.	THE	Pitch attitude (theta) at touchdown	degrees
25.	PHI	Roll attitude at touchdown	degrees

Twelve rows appear next which tabulate RMS, maximum and minimum values for ten parameters over the flight path segment from a glide slope height of 500 to 100 feet.

26.	AIRSPEED ERROR	Indicated airspeed minus V(APP)	knots

Table B-3

DATA ENTRIES OF THE SUMMARY PRINTOUT (con't)

Entry		Description	Units
27.	GNS ERROR	Groundspeed relative to GNS(REF)	knots
28.	GS DEV	Glide slope deviation as displayed	dots
29.	LOC DEV	Localizer deviation as displayed	dots
30.	VERT OFFSET	Aircraft vertical deviation from glide path (positive above glide path)	ft
31.	LAT OFFSET	Aircraft lateral deviation from localizer (positive right)	ft
32.	PITCH STR	Pitch steering bar position on pilot's ADI	bar widths
33.	ROLL STR	Roll steering bar position on pilot's ADI	bar widths
34.	ELEVATOR	Control column position (positive pitching up)	degrees
35.	AILERON	Control wheel position (positive right)	degrees
36.	ENERGY RATE	Same as 20	
37.	ACCEL MARGIN	Same as 21	

REFERENCES

1. W. B. Gartner and A. C. McTee, "Piloted Flight Simulator Study of Low-level Wind Shear, Phase 1," Report No. FAA-RD-77-166 by SRI International for U.S. DOT Federal Aviation Administration (May 1977).

2. W. B. Gartner, et al, "Piloted Flight Simulator Study of Low-level Wind Shear, Phase 2," Report No. FAA-RD-77-157 by SRI International for U.S. DOT Federal Aviation Administration (March 1977).